

Mesure de champs pour l'étude du bois et de ses dérivés Jean-Christophe Dupré, Pascal Doumalin



GDR 3544
Sciences du bois



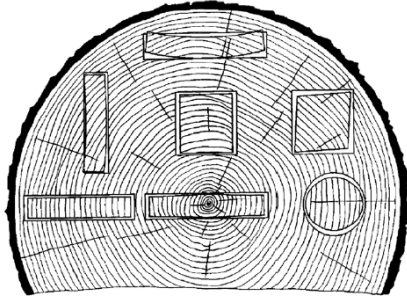
Workshop Bois et Imagerie 11 et 12 Mai

Axe PEM, Photomechanics and Experimental Mechanics

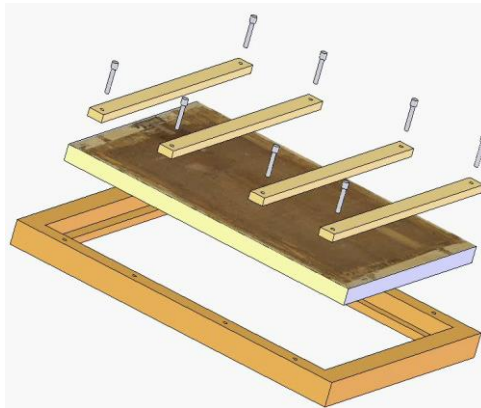
Fabrice Brémand, Pascal Doumalin, Jean-Christophe Dupré, Arnaud Germaneau, Franck Hesser and Valéry Valle

Site internet : www.pprime.fr

Adresse CNRS • Université de Poitiers • ENSMA • UPR 3346
SP2MI, Téléport 2, Boulevard Marie et Pierre Curie • BP 30179
F86962 FUTUROSCOPE CHASSENEUIL Cedex



Chargements hygroscopique,
thermique, mécanique... (couplés)
Avec face isolée... échelle macro,
meso, micro



Panneau peint, effet mécanique du
cadre, d'une restauration...



Etude de l'arbre sur pied



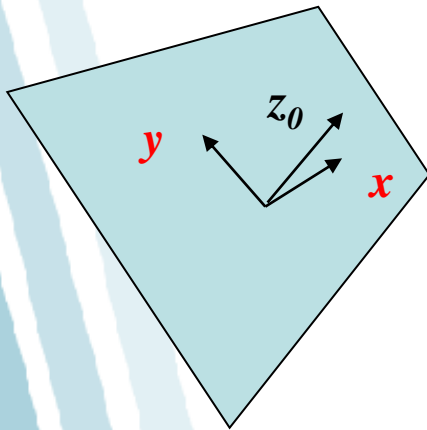
Comportement mécanique
de matériaux fibreux



Etude expérimentale du comportement mécanique d'une structure

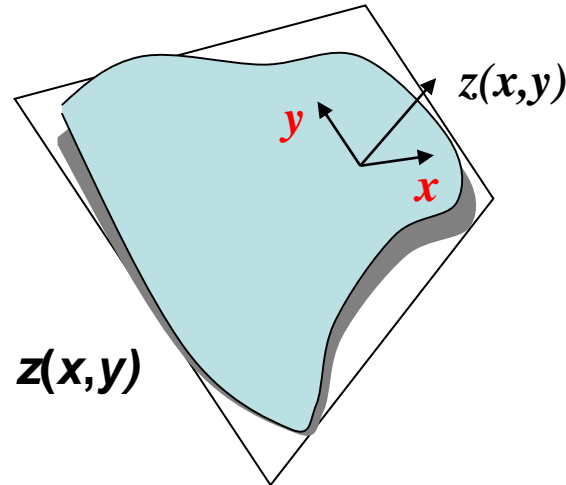
⇒ Mesure de grandeurs cinématiques (déplacements et/ou déformations)

Mesure 2D



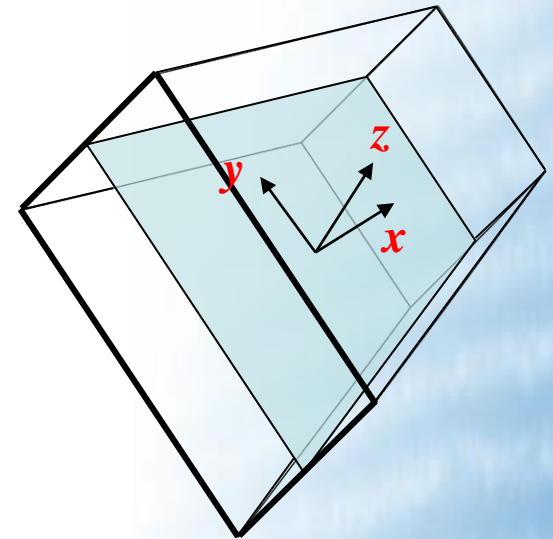
$$\begin{cases} u(x,y,z_0) \\ v(x,y,z_0) \end{cases}$$

Mesure 2D + déplacement hors plan (2D 1/2)



$$\begin{cases} u(x,y,z(x,y)) \\ v(x,y,z(x,y)) \\ w(x,y,z(x,y)) \end{cases}$$

Mesure 3D

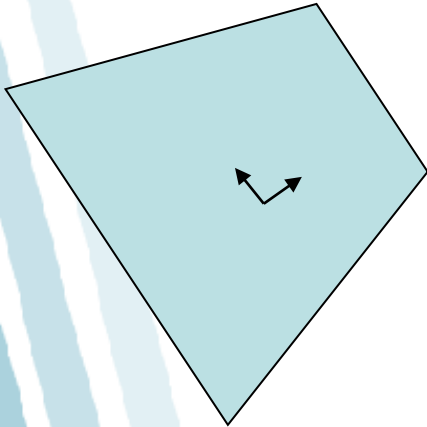


$$\begin{cases} u(x,y,z) \\ v(x,y,z) \\ w(x,y,z) \end{cases}$$

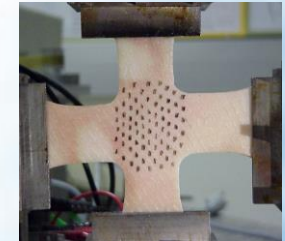
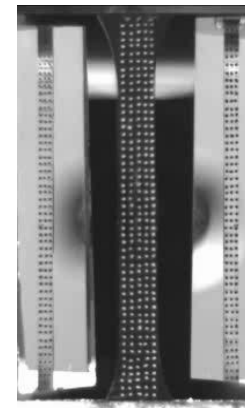


➤ Mesures 2D (surfactive)

1-corrélation d'images

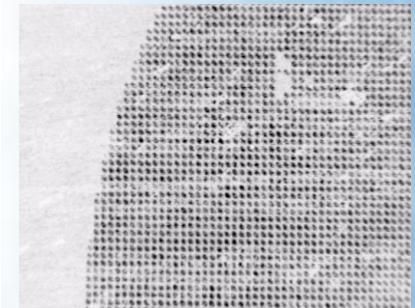


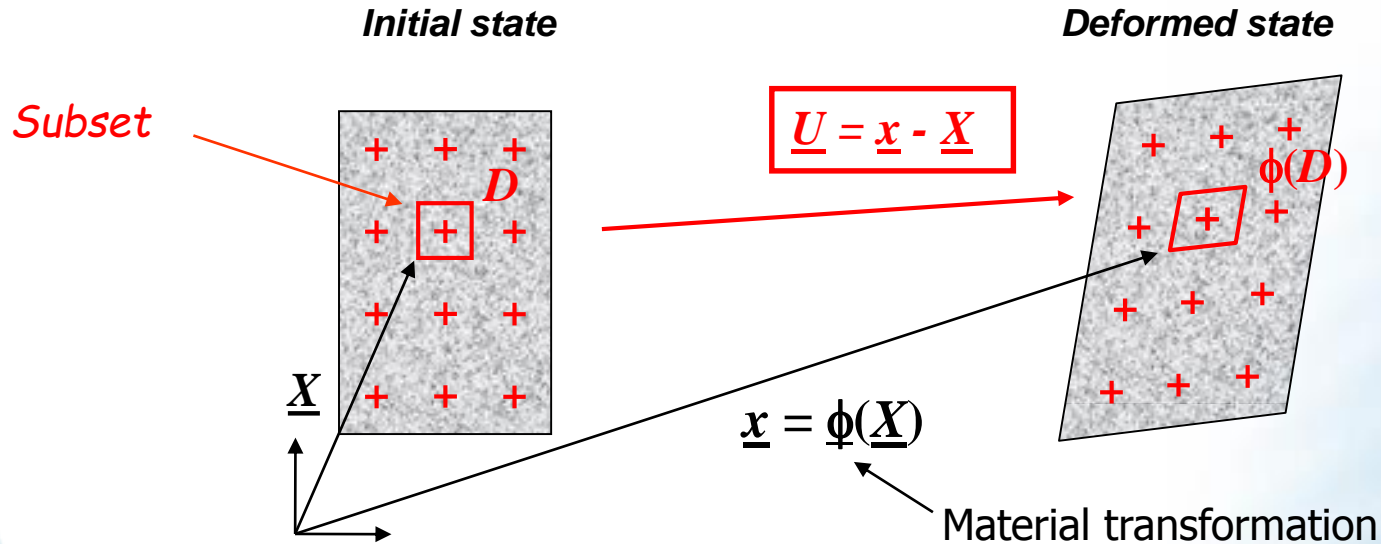
2-suivi de marqueurs



- Déplacements
- Déformations
- (Températures)
- (Contraintes)

3-analyse de réseau, grilles





- **Normalized** Correlation coefficient:

$$C = 1 - \frac{\sum_{\underline{X} \in D} (f(\underline{X}) - \bar{f}_D) \cdot (g(\phi(\underline{X})) - \bar{g}_D)}{\sqrt{\sum_{\underline{X} \in D} (f(\underline{X}) - \bar{f}_D)^2} \cdot \sqrt{\sum_{\underline{X} \in D} (g(\phi(\underline{X})) - \bar{g}_D)^2}}$$

Translation

$$\underline{\phi}(\underline{X}) = \underline{X} + \underline{T}$$

Translation + local gradient

$$\underline{\phi}(\underline{X}) = \underline{X} + \underline{T} + \frac{\partial U(\underline{X}_0)}{\partial \underline{X}} (\underline{X} - \underline{X}_0)$$

- **Subpixel measurement** : Interpolation of grey levels (bilinear, bi-cubic, spline...)

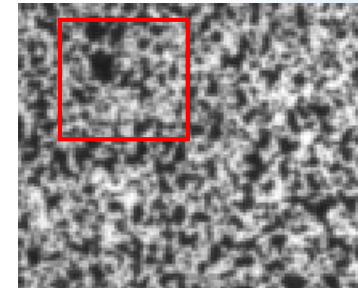
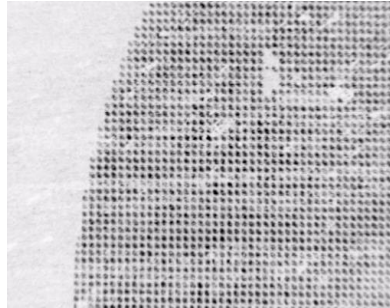
- Root mean square, First gradient minimization

Choice of pattern :

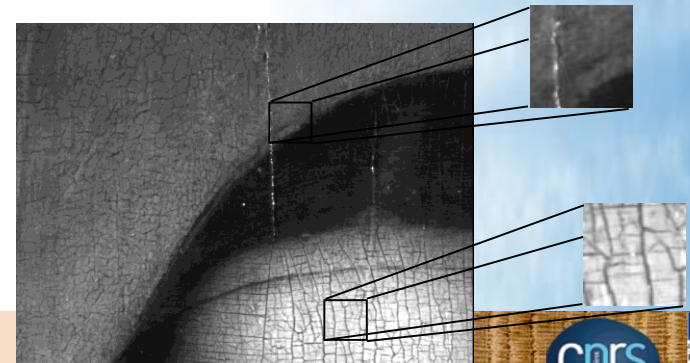
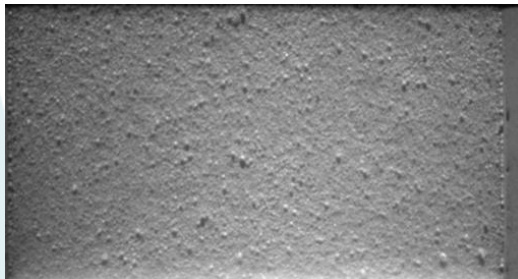
DIC performances function of the grey level distribution :

⇒ Artificial marks:

⇒ grid, lines, spots, random marks (speckle)



⇒ Natural marks (Surface of the specimen)

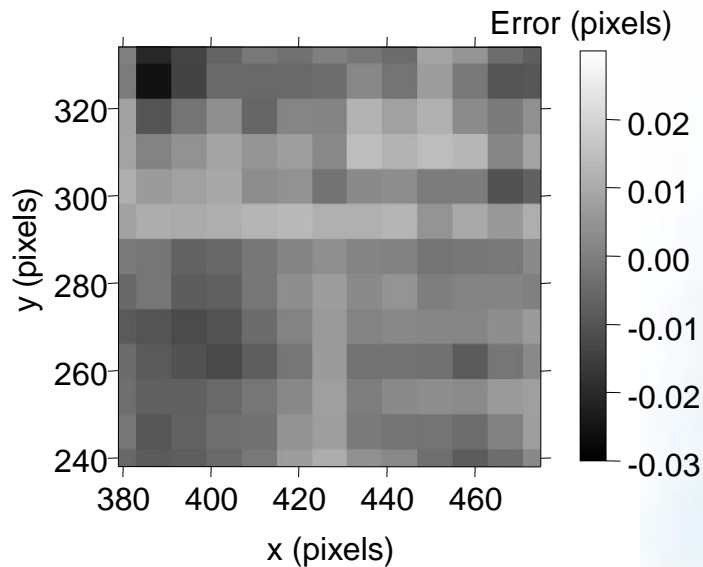




*Performances: displacement uncertainty
Imposed displacement test (by micro-stage translation)*

Error = measured displacement - imposed displacement

Map of error for a displacement:



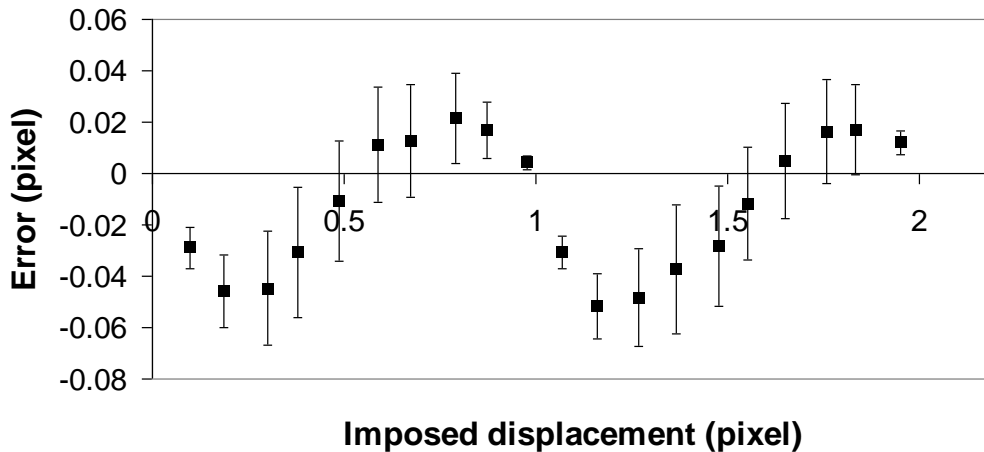
Calculation of average and standard deviation of gaps versus imposed displacement



Performances: displacement uncertainty

Systematic error : *Sinusoidal evolution* between 0 and 1 pixel

Random error : *maxi for displacement = 0.05 pixel*



Global uncertainty = 0.025 pixel

Uncertainty decreases when D increases

Uncertainty related to grain size, grey level gradient...

CNRS research group:

GDR 2519 Full field measurement and identification in solid mechanics,
 BORNERT M., et al, **Assessment of digital image correlation measurement errors: Methodology and results**
 Experimental Mechanics, 49(3) (2009).



Corrélation d'images (2D)

Mesure de déplacements et déformations surfaciques

Performances:

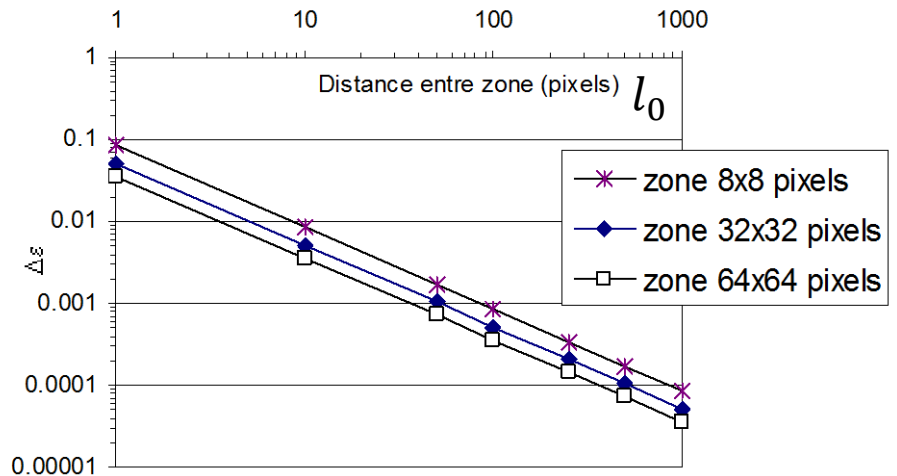
- ⇒ Dépend de la « **qualité** » du motif à corrélérer (gradient, contraste, taille du motif, variation entre deux images...)
- ⇒ Incertitude sur les déplacements \approx **0.02 pixels**

- ⇒ Incertitude sur les déformations:

$$\frac{\partial U}{\partial X} = \frac{U(X + l_0) - U(X - l_0)}{2l_0}$$

- ⇒ + Mesure sur un champ

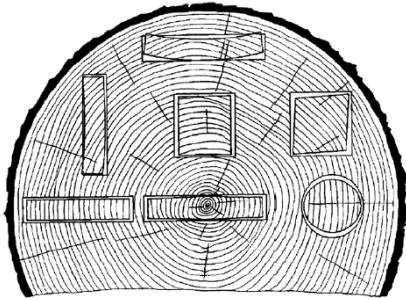
- ⇒ - Phénomène de **décorrél**ation pour de grandes déformations $>30\%$, contraste dégradé,...





Corrélation d'images

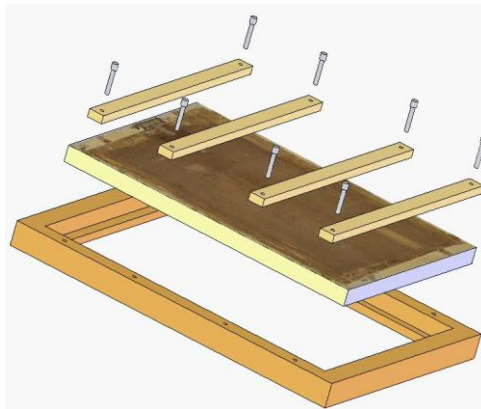
⇒ différentes applications



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Avec face isolée... échelle macro,
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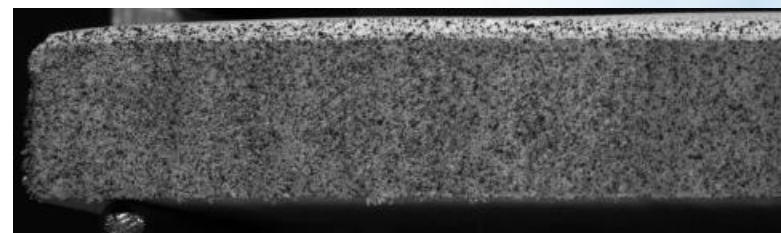
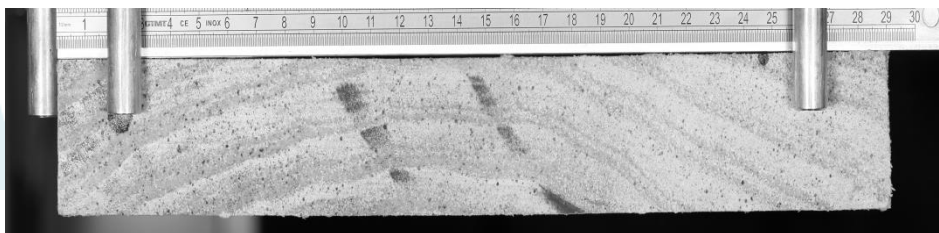
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Comportement mécanique
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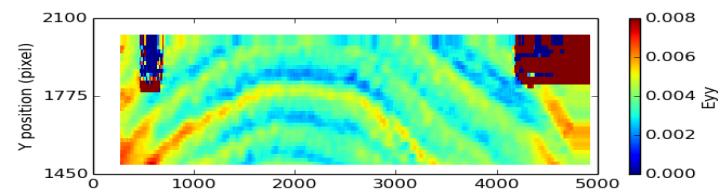
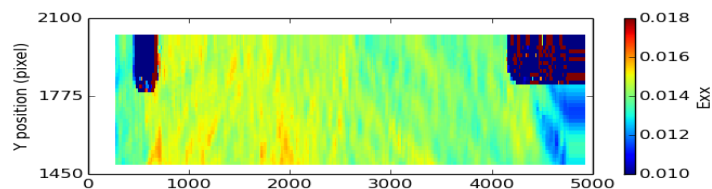
Chargement hygrothermique cyclique

Eprouvette sur dosse 90% HR ref 75% HR,
50°C.

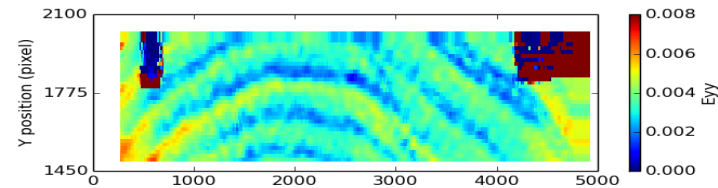
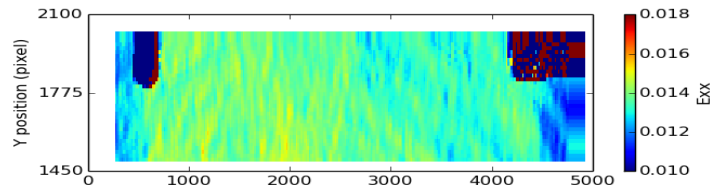


Cécilia Gauvin (thèse Univ. Montpellier 2015)

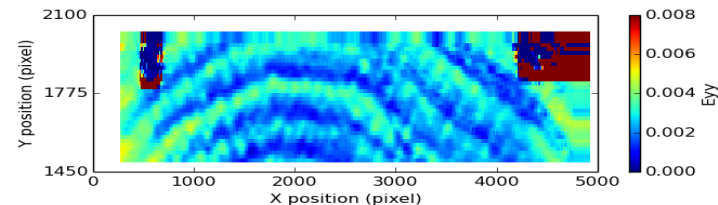
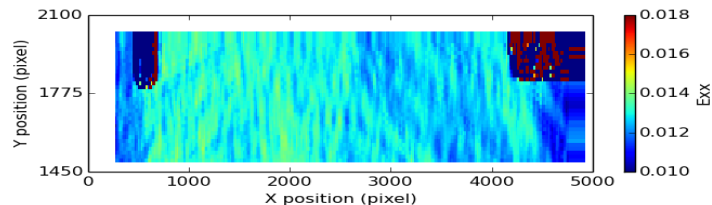
1 cycle



5 cycles

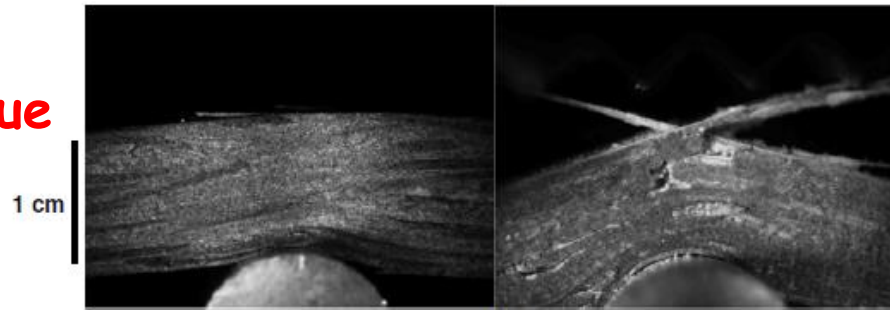


9 cycles



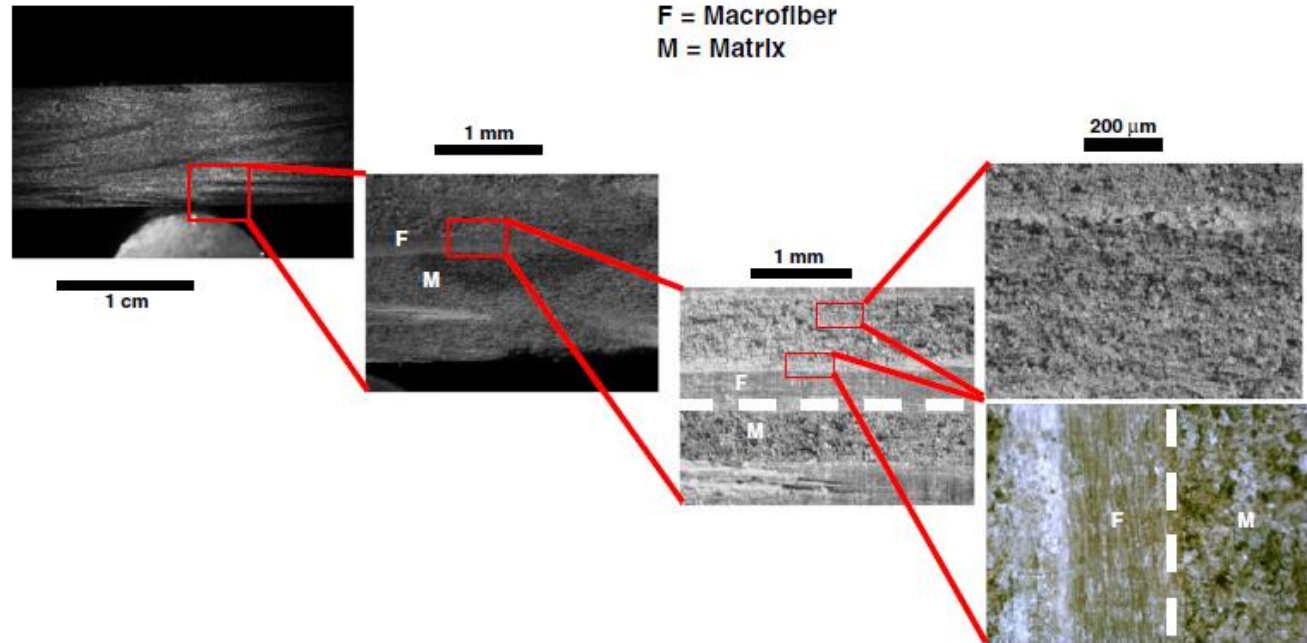
Chargement mécanique

Essais de Flexion 3 points sur des éprouvettes en palmer
Relation structure-déformation, fissuration



(b)

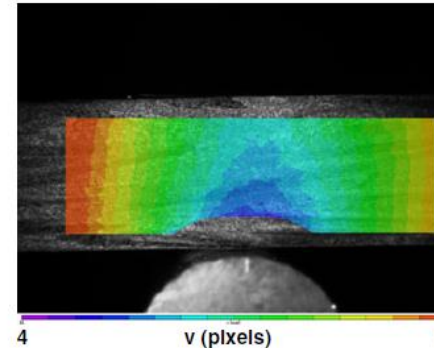
F = Macrofibrer
M = Matrix



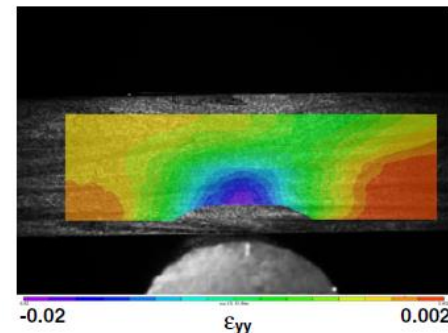
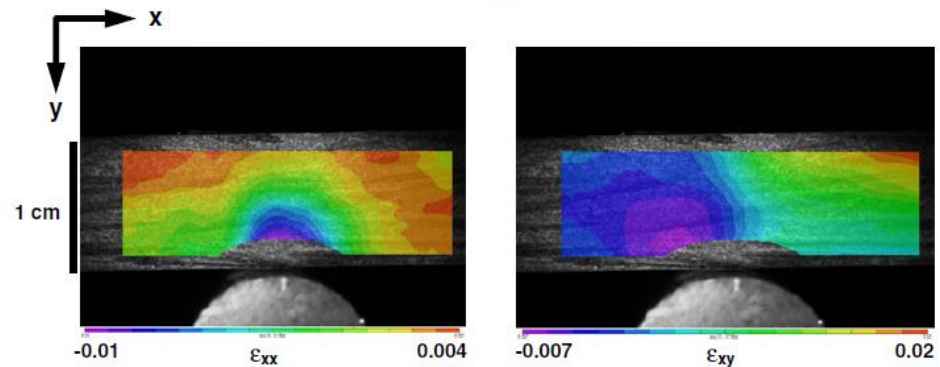
(c)

Chargement mécanique

Essais de Flexion 3 points sur des éprouvettes en palmier
Relation structure-déformation, fissuration



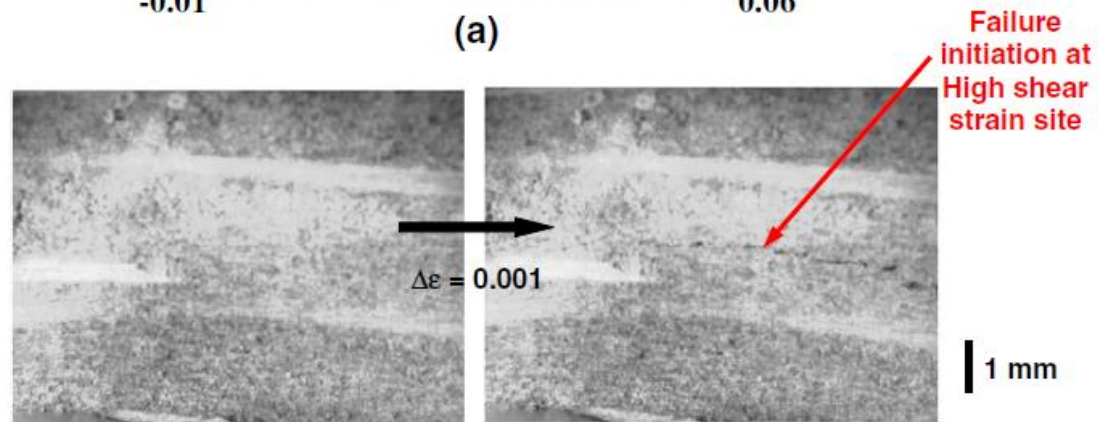
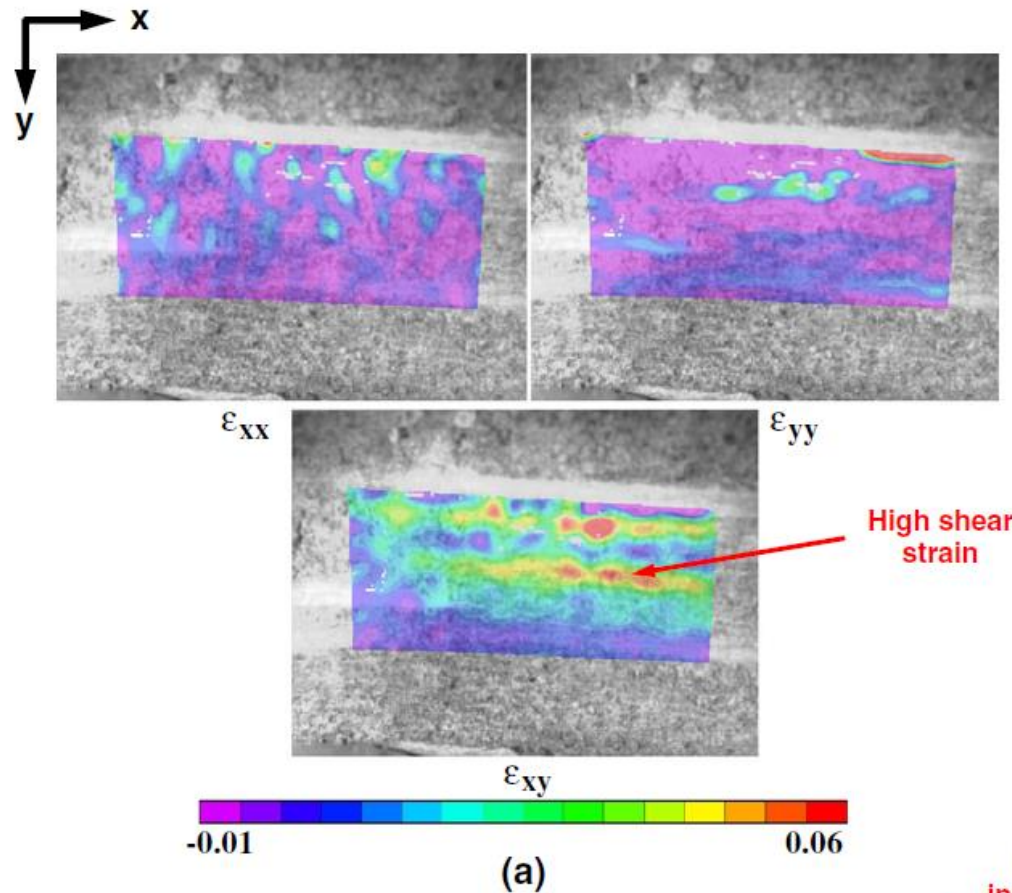
(a)



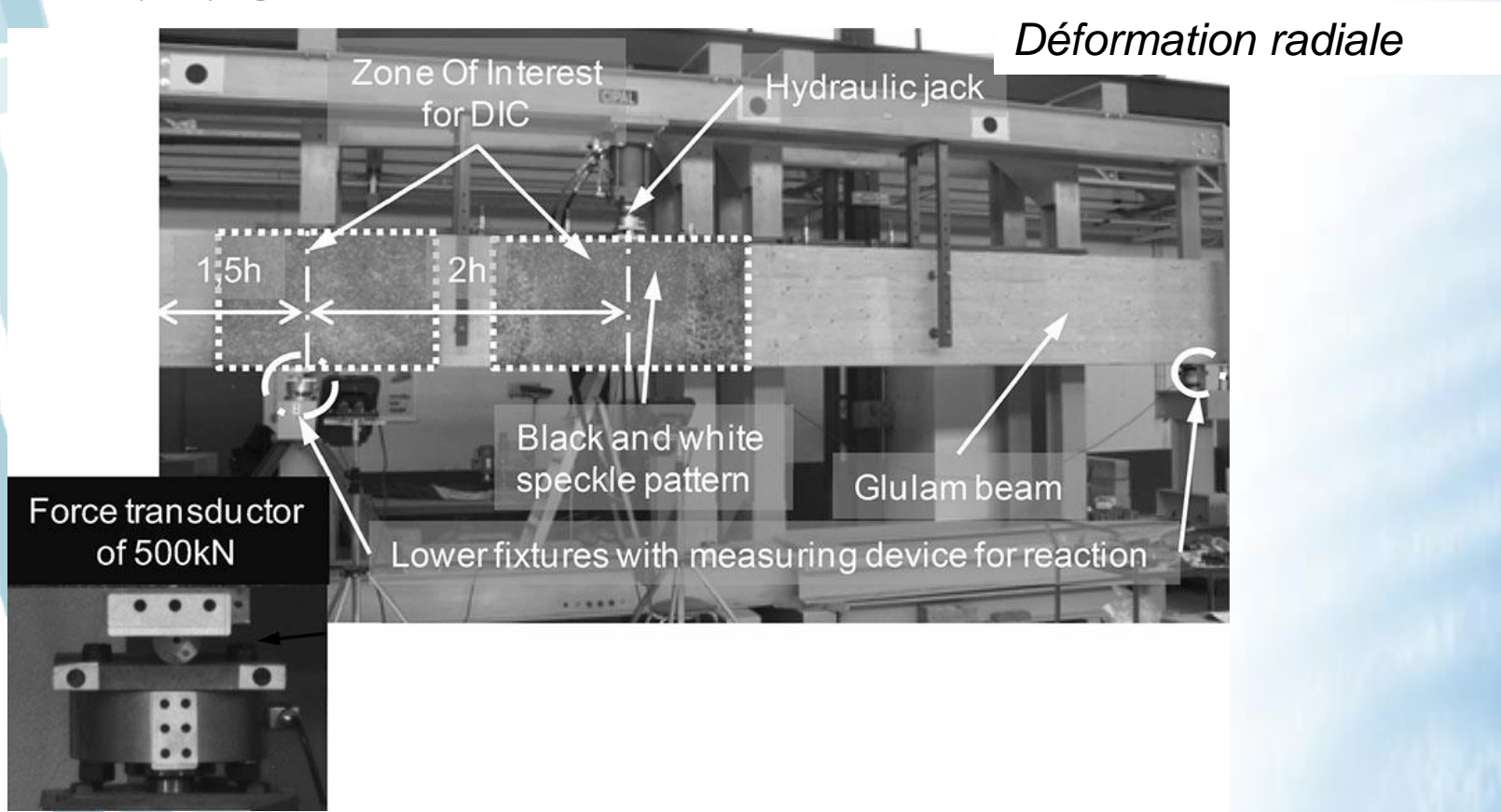


Chargement mé

Essais de Flexion
points sur des
éprouvettes en pa
Relation structure-
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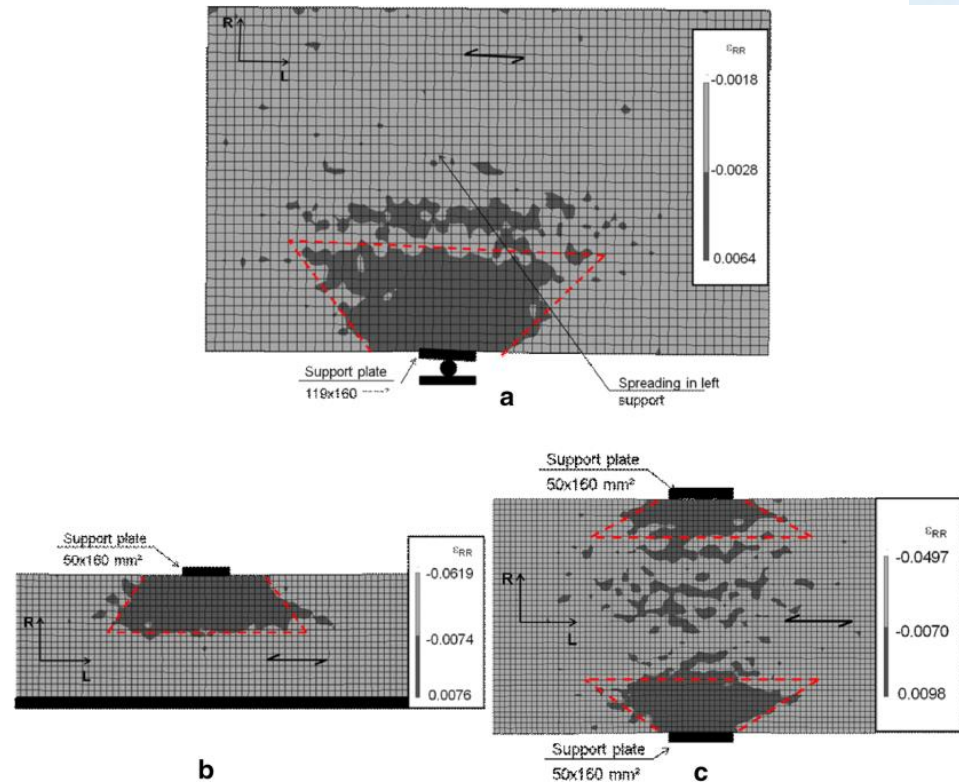
Bois de construction stratifié collé: étude des localisations et de propagation des contraintes (flexion)



Spreading of transverse compressive stresses in glued laminated timber, D, Lathuilliere O. Pop, L. Bléron, F. Dubois, F. Fouchal, JF Bocquet, Eur. J. Wood Prod. (2015)

Bois de construction stratifié collé: étude des localisations et de propagation des contraintes (flexion)

Déformation radiale



Spreading of transverse compressive stresses in glued laminated timber, D, Lathuilliere O. Pop, L. Bléron, F. Dubois, F. Fouchal, JF Bocquet, *Eur. J. Wood Prod.* (2015)



Etude

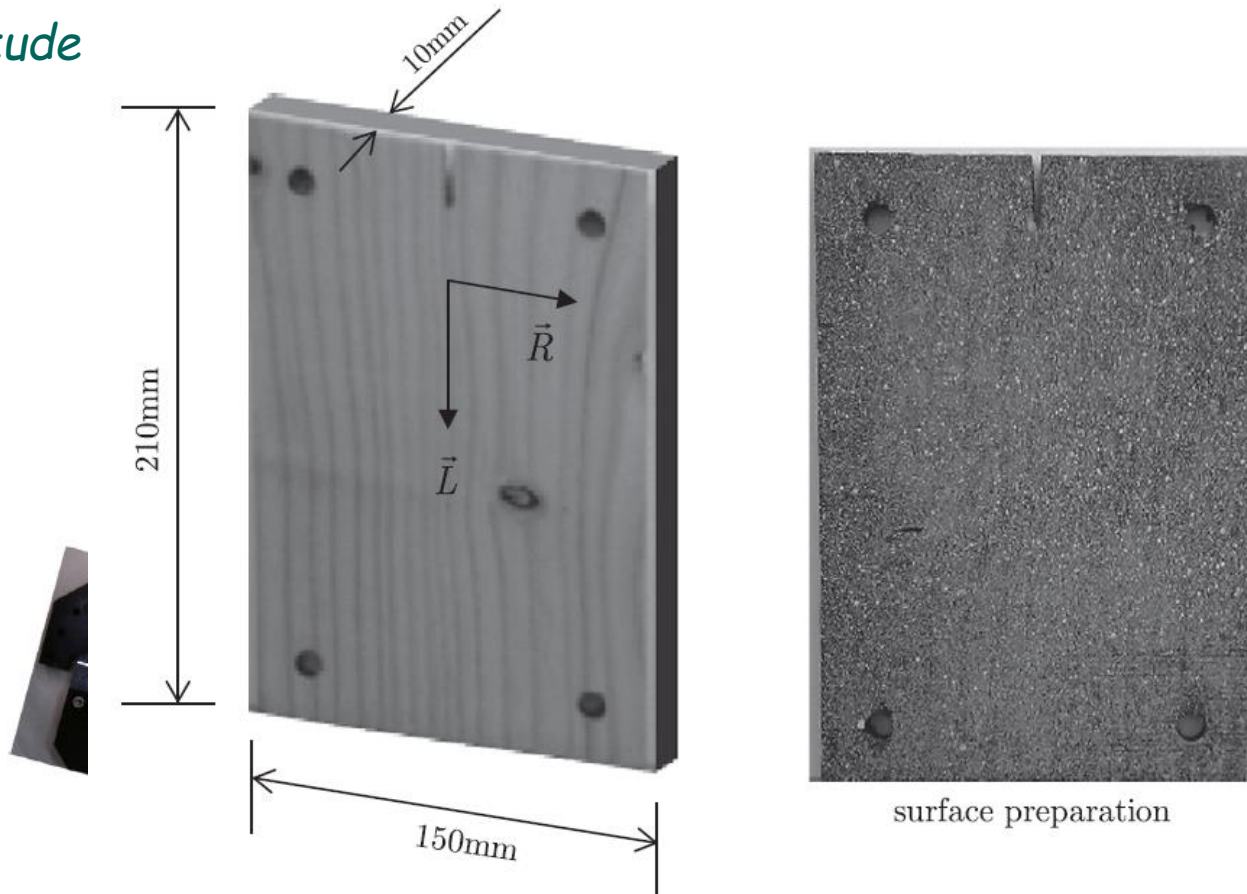


Fig. 1. A Douglas fir specimen and its random black-and-white pattern preparation.



Fig. 8. Mixed-mode loading configurations.

Mixed mode fracture properties characterization for wood by
 Digital Images Correlation and Finite Element Method coupling
 M. Méité, F. Dubois, O. Pop, J. Absi, Engineering Fracture Mechanics 2013



Etude

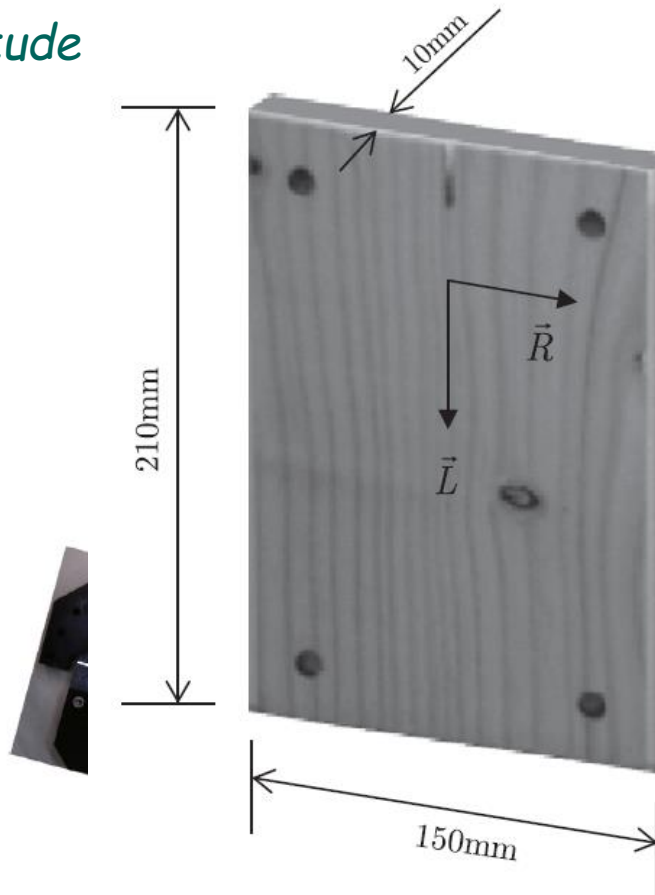


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Fig. 8. Mixed-mode loading configurations.

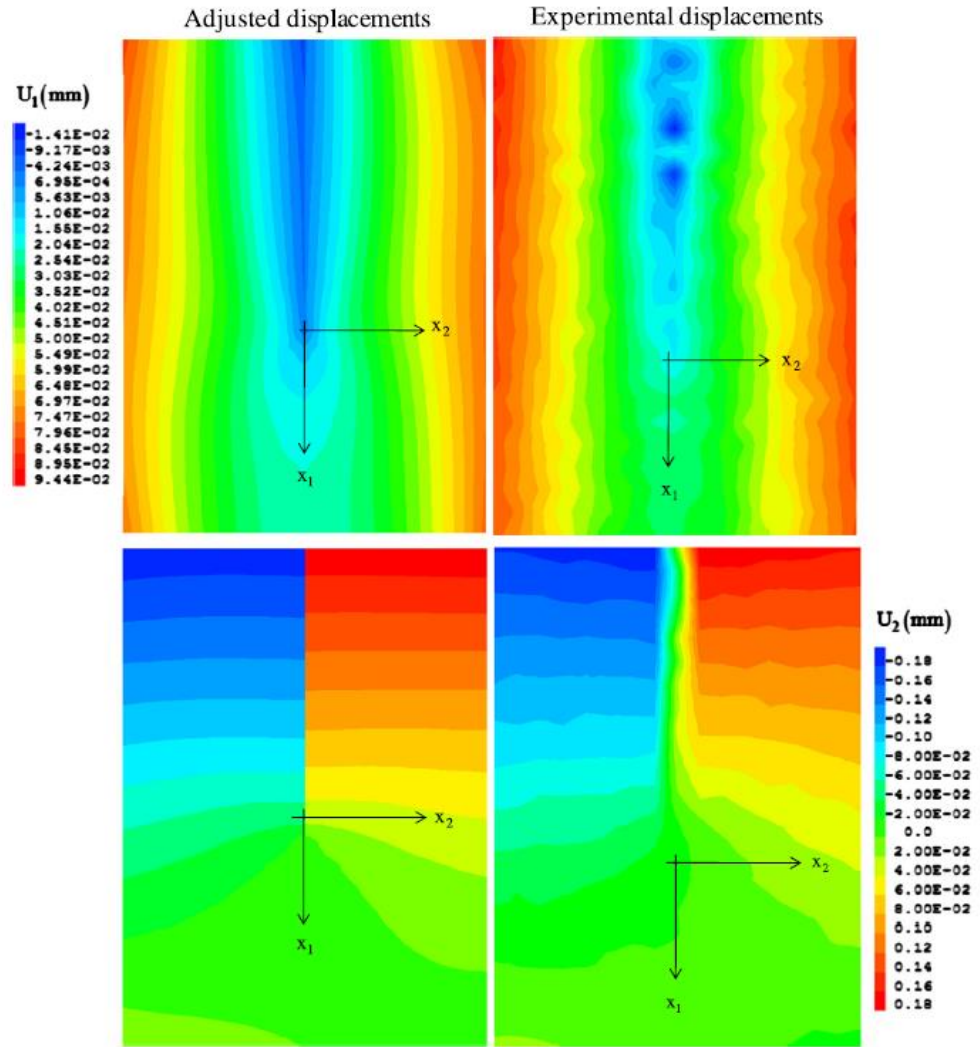


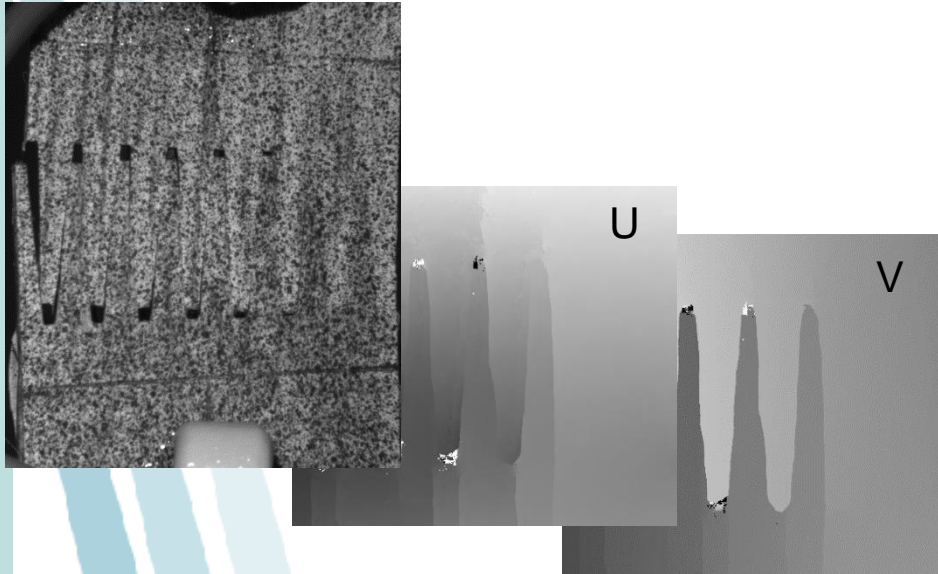
Fig. 9. Experimental and adjusted displacement fields, with $\beta = 0^\circ$.

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Discontinuité, fissuration, adaptation de la transformation

Exemple : Assemblage collé
(Collaboration GEMH)

Image déformée



Transformation

$$x^* = x - u - \frac{du}{dx}x - \frac{du}{dy}y$$

$$y^* = y - v - \frac{dv}{dx}x - \frac{dv}{dy}y$$

$$\sum_k u_k H_k(x, y)$$

$$\sum_k v_k H_k(x, y)$$

Corrélation Classique

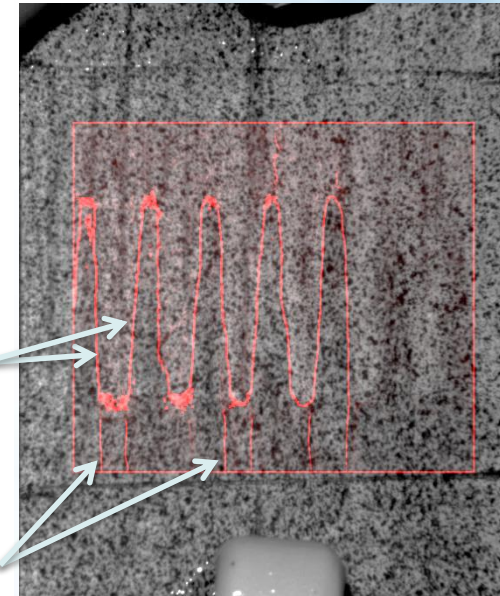
H-DIC
(XCorrel)

$$\langle \varepsilon \rangle = \frac{|\langle \varepsilon_1 \rangle - \langle \varepsilon_2 \rangle|}{2}$$

Pseudo
déformation

Décollements

Fractures



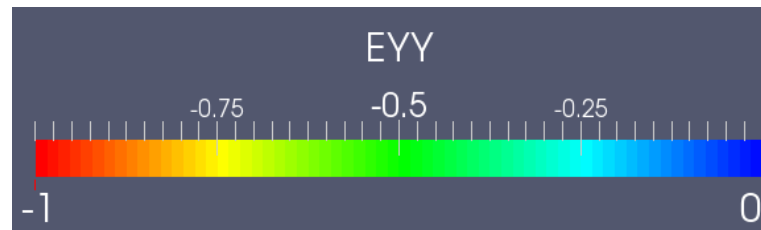
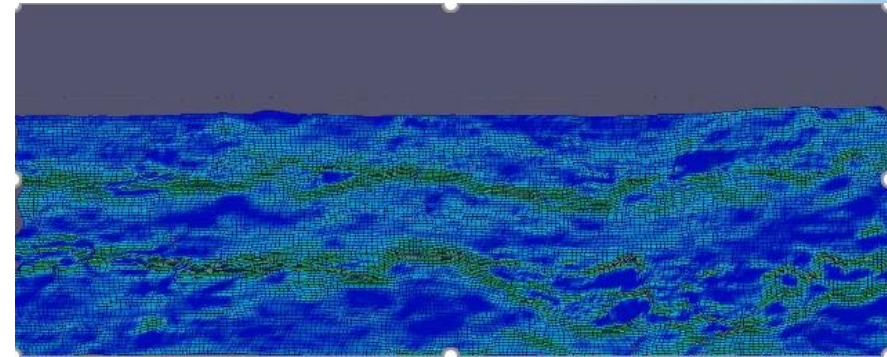
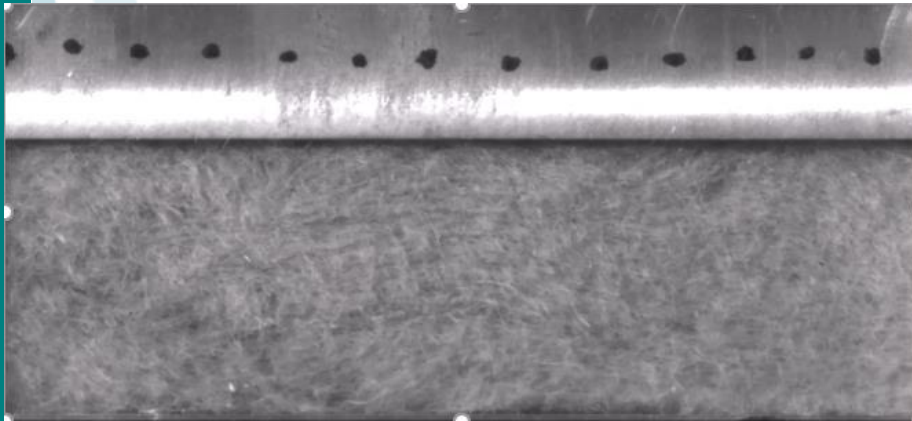


Panneau isolant fibres bois/PES

Pin maritime...

Projet Ademe Ecomatfib

-> Etude du comportement mécanique sous **compression** et **reprise** en épaisseur

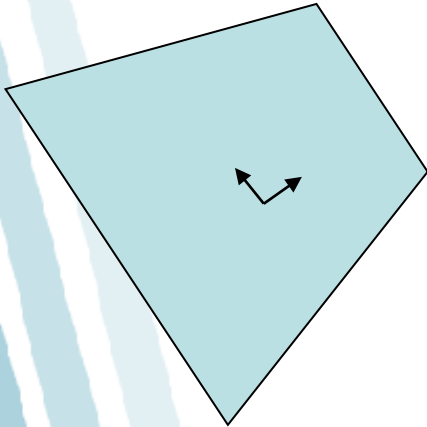


Déformation
verticale

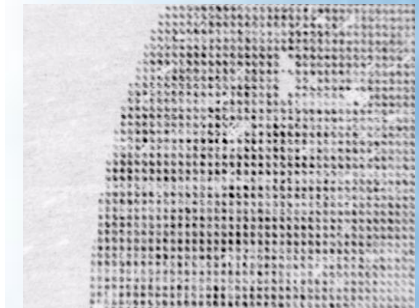
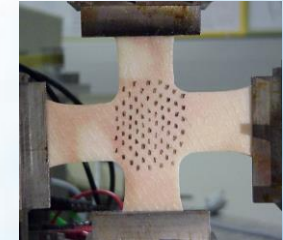
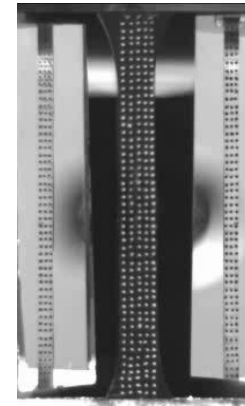
H. Tran, P. Doumalin, C. Delisée, J.C. Dupré, J. Malvesto, A. Germaneau, 3D mechanical analysis of low-density wood based fiberboards using X-ray microcomputed tomography and Digital Volume Correlation, *Journal of Materials Science*, 48, 2013

➔ • Mesures 2D (surfactive)

1-corrélation d'images



2-suivi de marqueurs

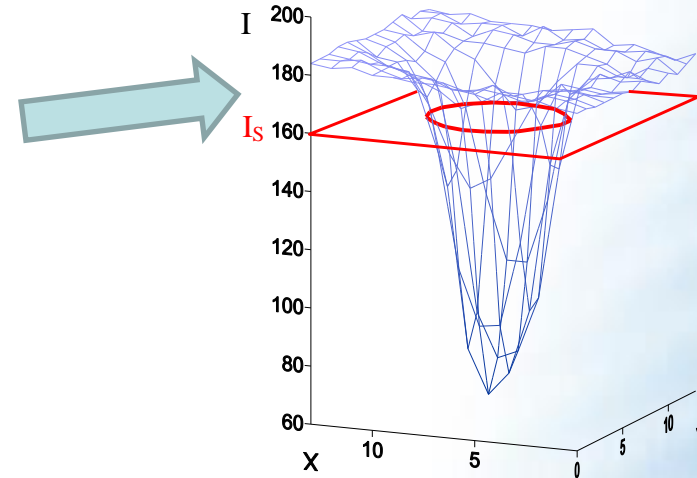
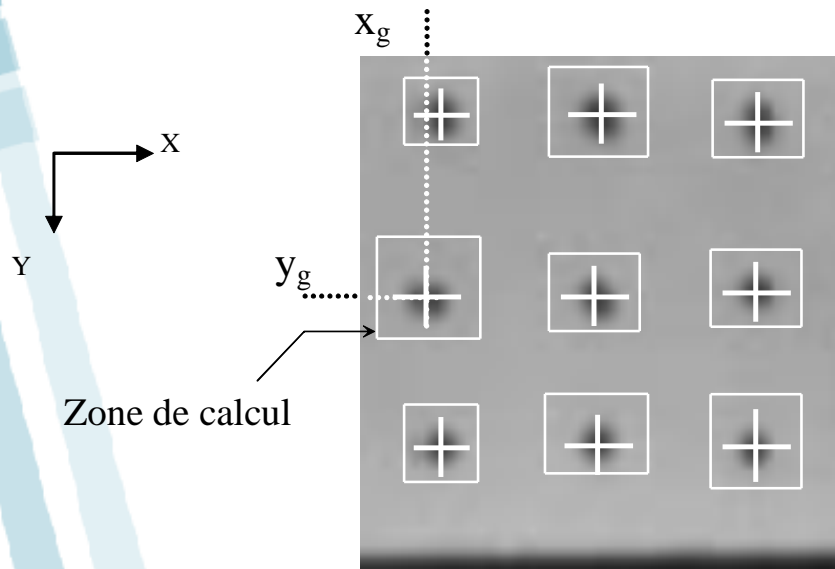


3-analyse de réseau, grilles

- Déplacements
- Déformations
- (Températures)
- (Contraintes)

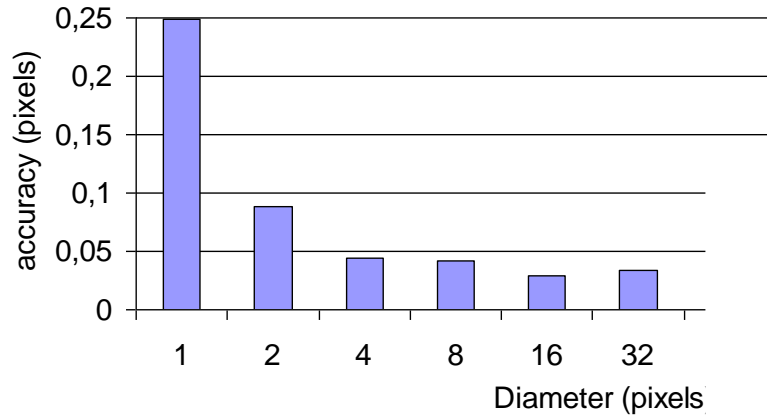


Calcul de la position des marqueurs:



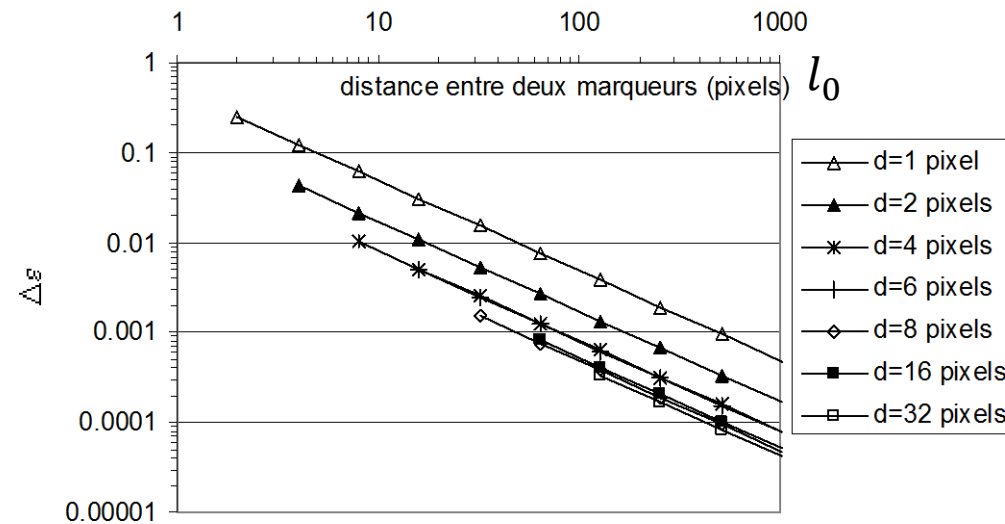
$$\left\{ \begin{array}{l} x_g = \frac{\sum_i x_i (I_i - I_s)}{\sum_i (I_i - I_s)} \\ y_g = \frac{\sum_i y_i (I_i - I_s)}{\sum_i (I_i - I_s)} \end{array} \right.$$

Précision fonction du diamètre des marqueurs



$$\frac{\partial U}{\partial X} = \frac{U(X + l_0) - U(X - l_0)}{2l_0}$$

Incertitude sur les déformations:



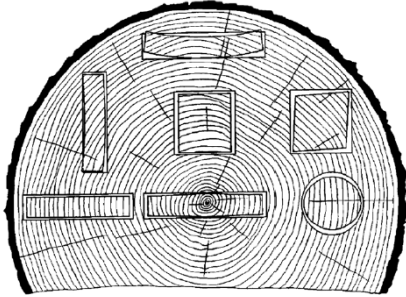
+ Grande déformation, **Robustesse**, **facilité**, rapidité d'analyse

- **Base de mesure** importante, **fixée** avant l'essai, dépôt de marqueurs



Suivi de marqueurs

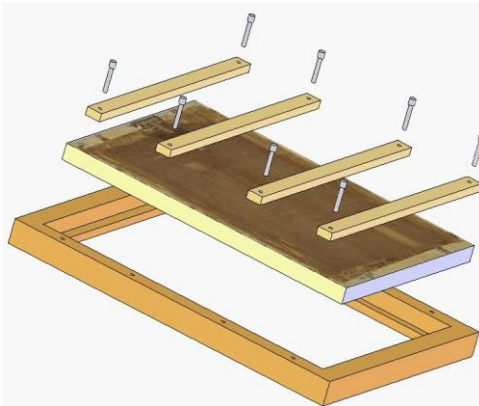
⇒ différentes applications



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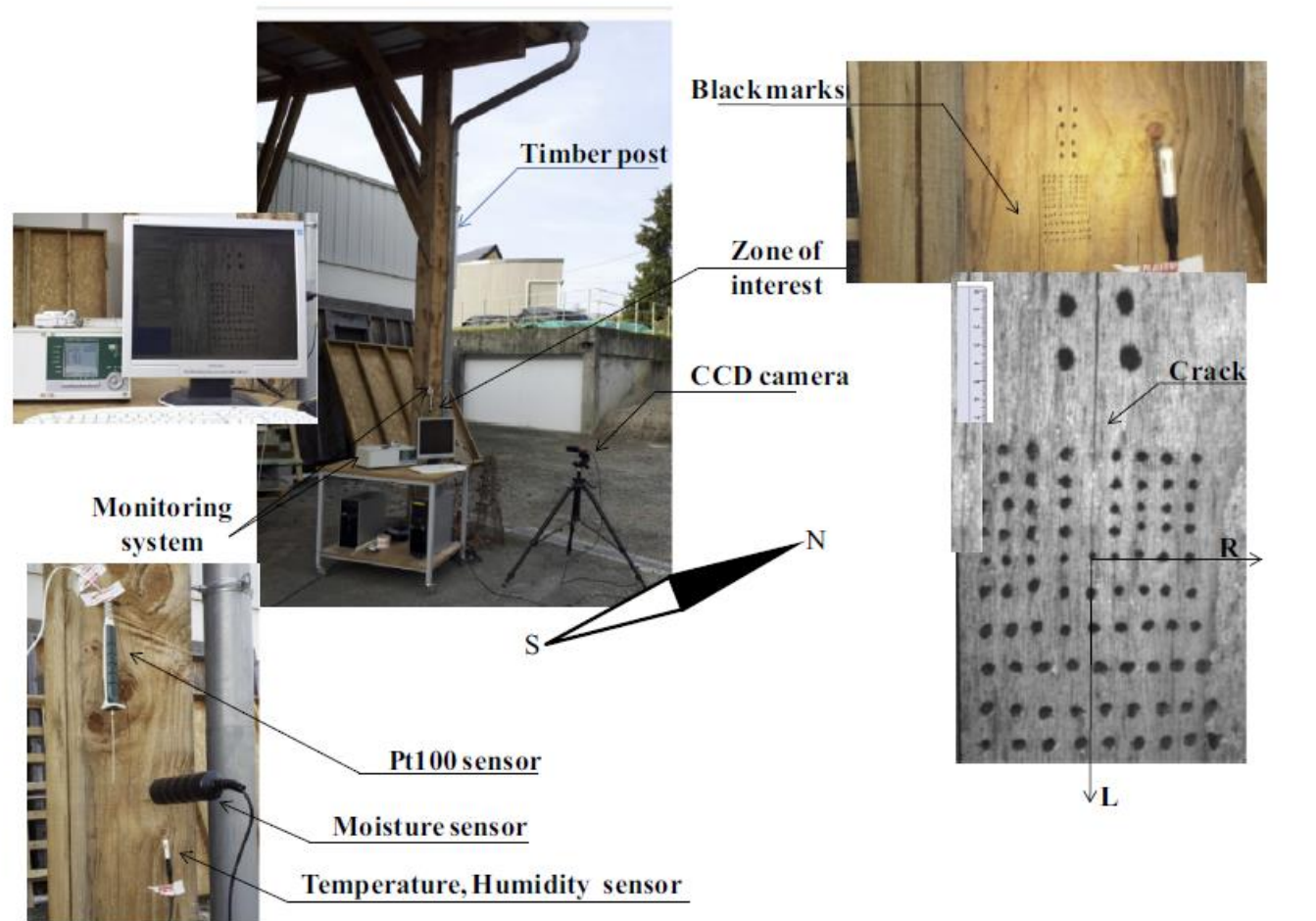


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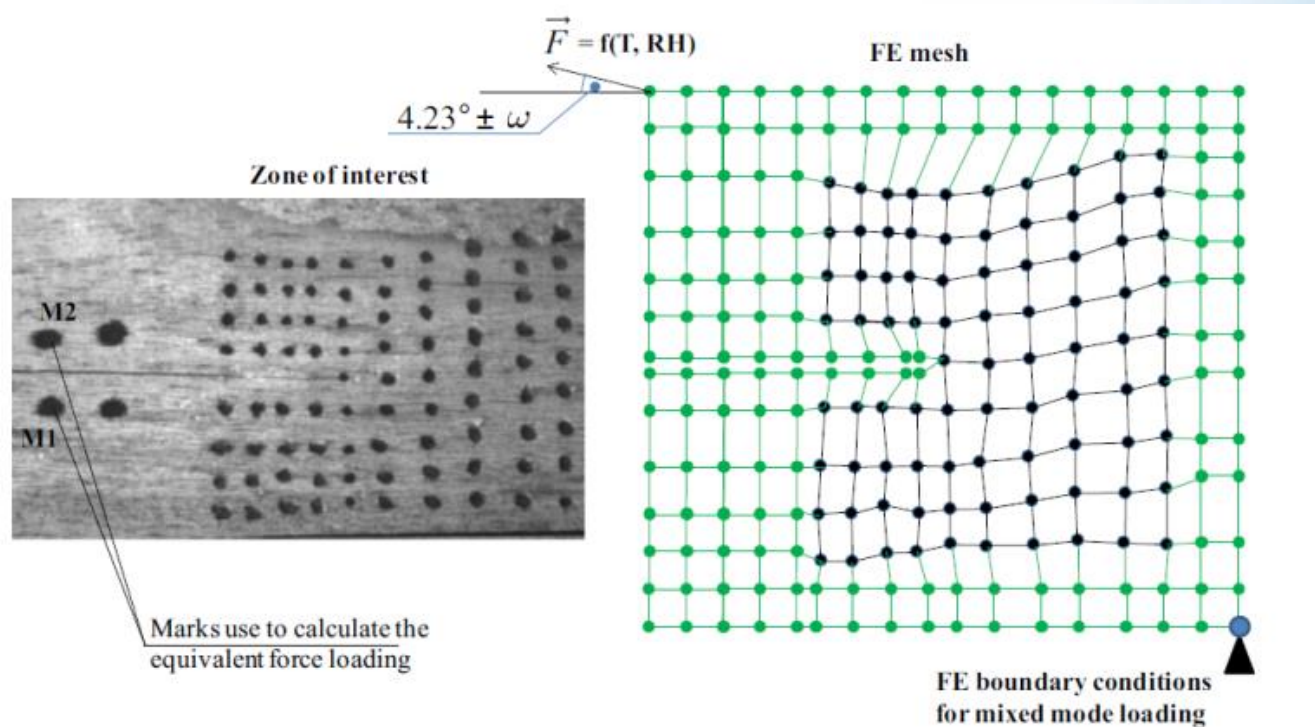
Comportement mécanique
de matériaux fibreux

Bois de construction,
étude de fissuration en
mode mixte



Determination of timber material fracture parameters using mark tracking method; O. Pop, F. Dubois, *Construction and Building Materials*, 2016

Bois de construction,
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Determination of timber material fracture parameters using mark tracking method; O. Pop, F. Dubois, Construction and Building Materials, 2016

Etude de la verse du Peuplier (IDF, LRBB, I2M)

Différentes **difficultés**

🔔 **Mesure in-situ**

extérieur (conditions climatiques)

🔔 **Grands objets**

Recul suffisant: point de vue adapté, objectif adapté

🔔 **Méthode de mesure robuste**

⇒ **Adaptation du Suivi de marqueurs**



E. Robin, J. C. Dupré, F. Brémand, "Détermination de la déformée du tronc et des caractéristiques mécaniques des racines de peupliers par méthodes optiques", CFM, 2003, Nice

Etude de la verse du Peuplier (IDF, LRBB, I2M)

Différentes difficultés

🔔 Mesure in-situ

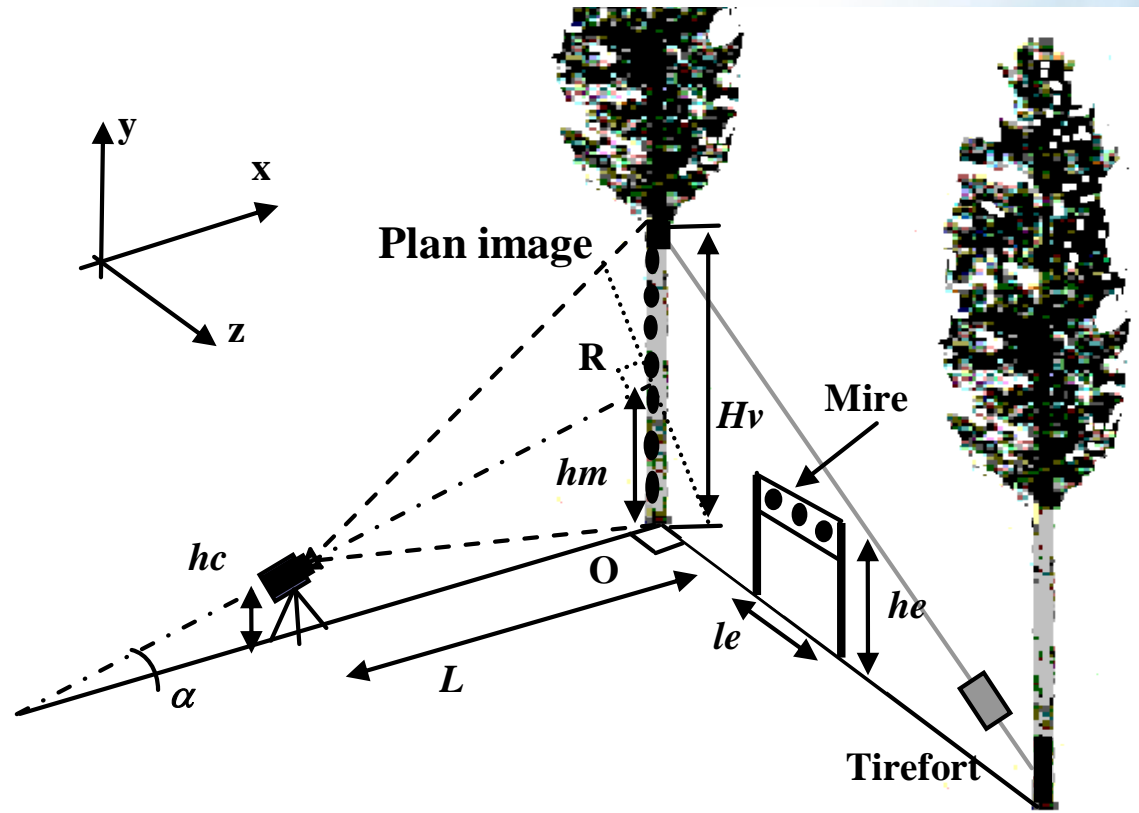
extérieur

🔔 Grands objets

Recul suffisant: pc

🔔 Méthode de mesure rc

⇒ Adaptation du Suivi



E. Robin, J. C. Dupré, F. Brémand, "Détermination de la déformée du tronc et des caractéristiques mécaniques des racines de peupliers par méthodes optiques", CFM, 2003, Nice

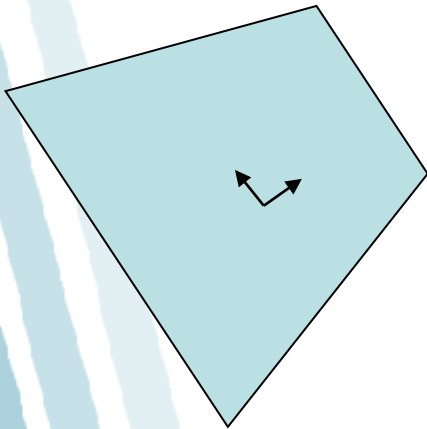
Etude la verse du Peuplier (IDF, LRBB, I2M)



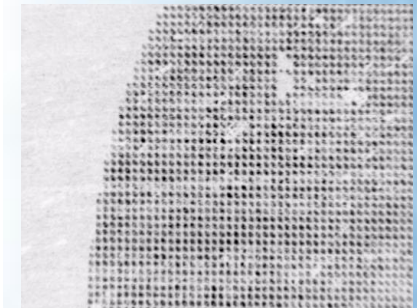
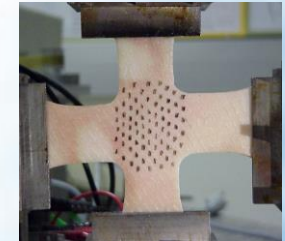
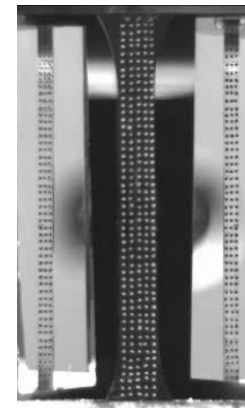
E. Robin, J. C. Dupré, F. Brémand, "Détermination de la déformée du tronc et des caractéristiques mécaniques des racines de peupliers par méthodes optiques", CFM, 2003, Nice

➔ • Mesures 2D (surfactive)

1-corrélation d'images



2-suivi de marqueurs

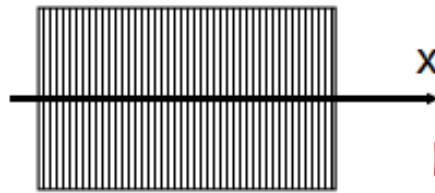


- Déplacements
- Déformations
- (Températures)
- (Contraintes)

3-analyse de réseau, grilles



Analyse de réseau, grilles (moiré, TF, décalage de phase...)



$$I(x) = I_0(x) + I_1(x) \sin(\Phi(x))$$

$$\text{Déplacement} = u(x) = \frac{p}{2\pi} (\Phi_{def}(x) - \Phi_{ini}(x))$$

⇒ Décalage de phase (spatial)

Surrel, J; Surrel, Y, *The fringe projection technique for shape acquisition of live biological objects*, JOURNAL OF OPTICS, 1998

⇒ Analyse par WFT

Extraire la phase des images : transformée de Fourier (enveloppe gaussienne)

$$\Phi = \text{atan} \left(\frac{J}{R} \right) \quad \begin{cases} R(x) = \frac{1}{\sigma\sqrt{2\pi}} \times \int_{-\infty}^{+\infty} s(u) \exp\left(\frac{-(u-x)^2}{2\sigma^2}\right) \cos(\omega u) du \\ J(x) = \frac{1}{\sigma\sqrt{2\pi}} \times \int_{-\infty}^{+\infty} s(u) \exp\left(\frac{-(u-x)^2}{2\sigma^2}\right) \sin(\omega u) du \end{cases}$$

Trouver des déformations à partir des cartes de phases lissées (méthode classique) :

Approche proposée: dériver la phase directement de

$$\frac{d\Phi}{dx} = \Phi' = \frac{d}{dx} \text{atan} \left(\frac{J}{R} \right) = \frac{J'R - JR'}{R^2 + J^2}$$

C. Badulescu, M. Grédiac, J.-D. Mathias, *Investigation of the grid method for accurate in-plane strain Measurement*, Measurement Science and Technology, 2009

Etendue au cas 2D



Performance (WFT): 100 μ strain, base de mesure: 30 pixels (pas de 5 traits/mm et grandissement de 1 mm/pixel)

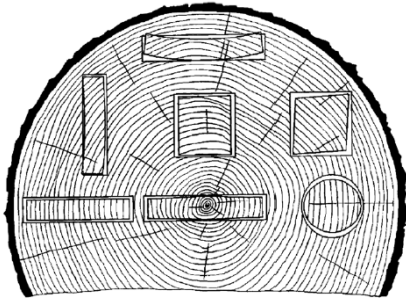
+ **Analyse:** pas de déroulage de phase, aucun lissage direct de carte de déplacement et de dérivation des déplacements

- **Dépôt** des grilles, zone d'étude relativement petite



Méthode de grilles

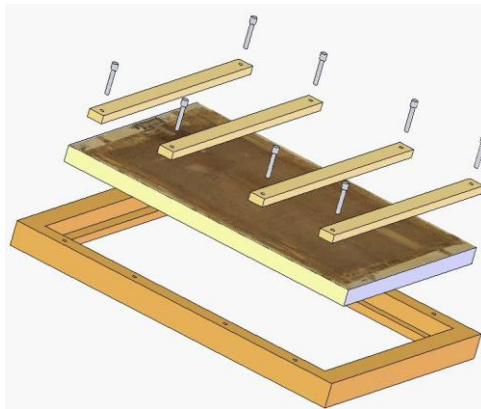
⇒ différentes applications



Chargements hygroscopique,
thermique, mécanique... (couplés)
Avec face isolée... échelle macro,
meso, micro



Etude de l'arbre sur pied



Panneau peint, effet mécanique du
cadre, d'une restauration...

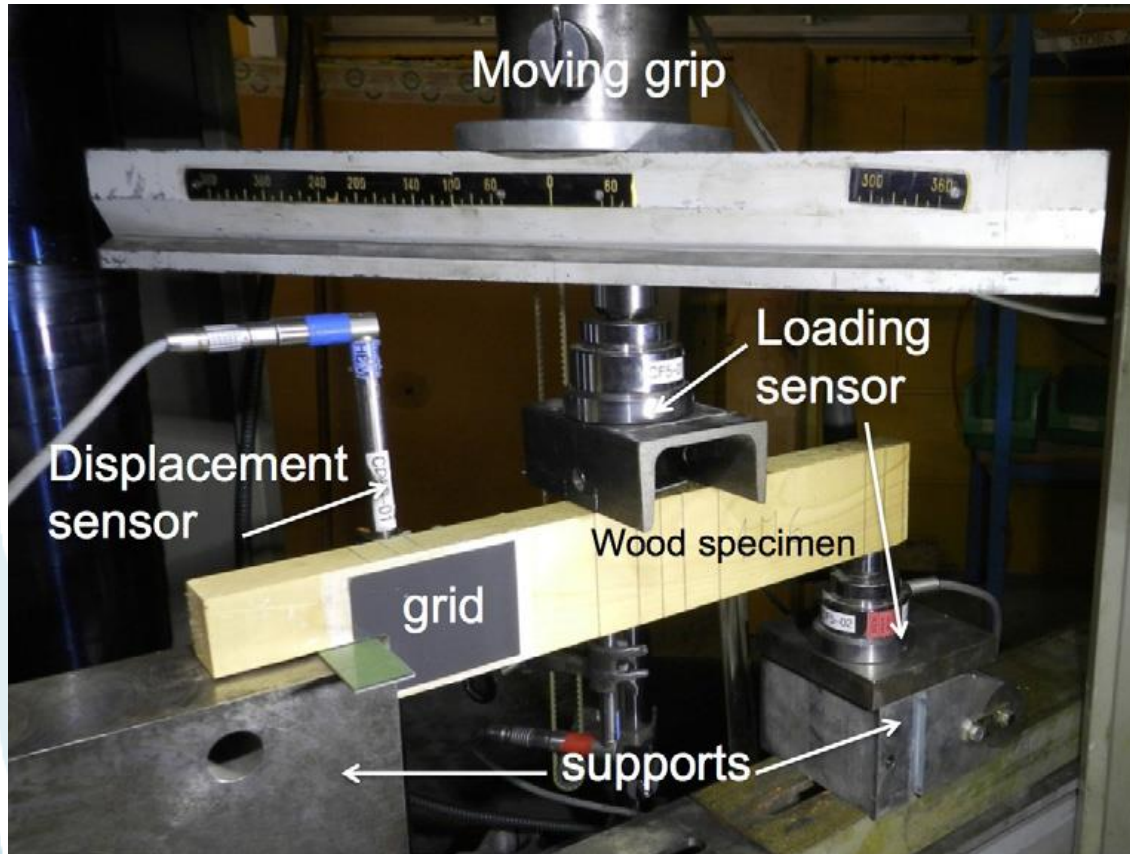


Comportement mécanique
de matériaux fibreux



Comportement mécanique de poutre en flexion:

Grille déposée par transfert (pas de 0.2 mm)



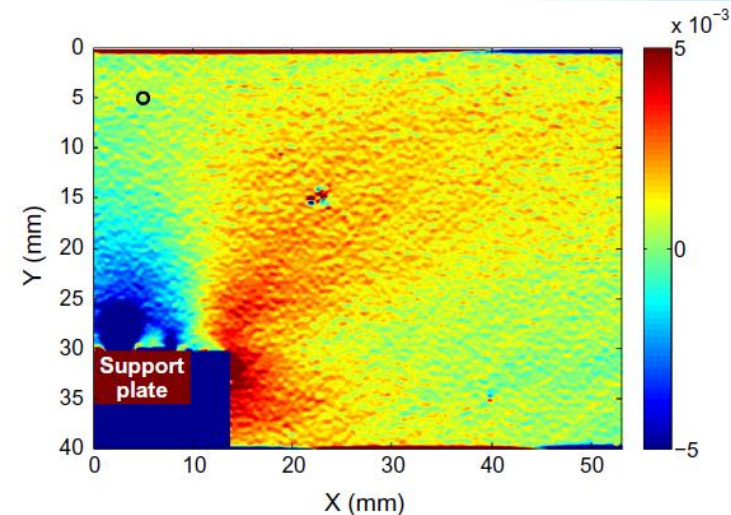
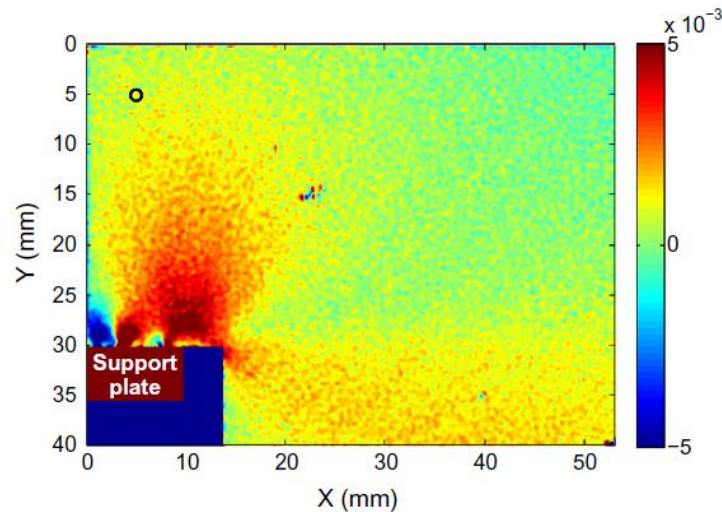
Studying the mechanical behavior of notched wood beams using full-field measurements

E. Toussaint, E. Fournely, R. Moutou Pitti, M. Grédiac, Engineering Structures, 2016



Comportement mécanique de poutre en flexion:

Grille déposée par transfert (pas de 0.2 mm)



Studying the mechanical behavior of notched wood beams using full-field measurements

E. Toussaint, E. Fournely, R. Moutou Pitti, M. Grédiac, Engineering Structures, 2016



Essai de flexion, identification matrice de rigidité

Pin maritime .

$80 \times 20 \times 5 \text{ mm}^3$

Grille déposée par transfert (pas de
 0.1 mm)

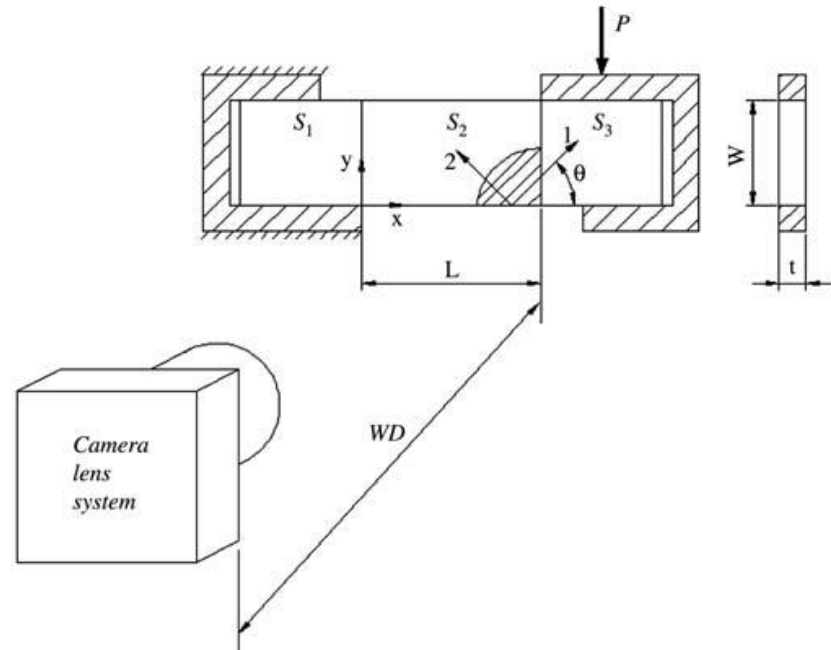
a



R

L

c



b



Novel experimental approach for longitudinal-radial stiffness
characterisation of clear wood by a single test

J.Xavier, S.Avril, F. Pierron and J. Morais, *Holzforschung*, 2007

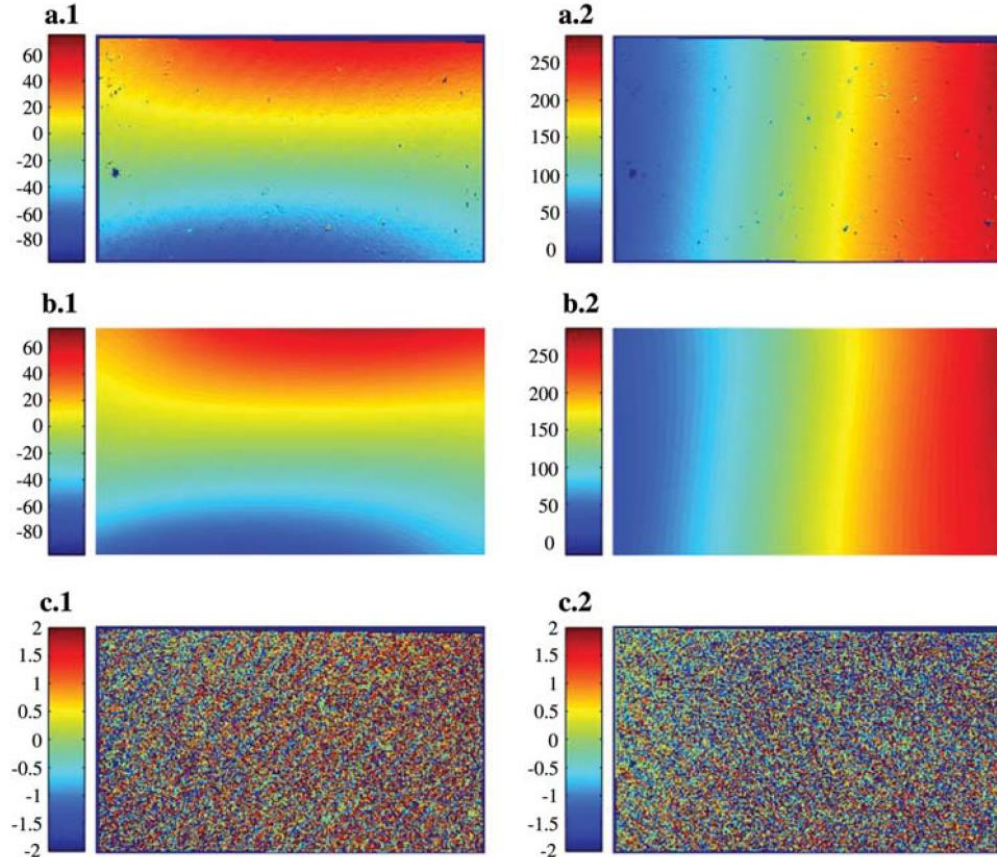


Essai de flexion, identification matrice de rigidité

Pin maritime .

$80 \times 20 \times 5 \text{ mm}^3$

*Grille déposée par transfert (pas de
0.1 mm)*



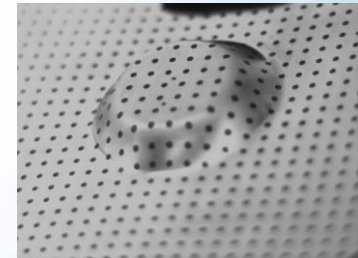
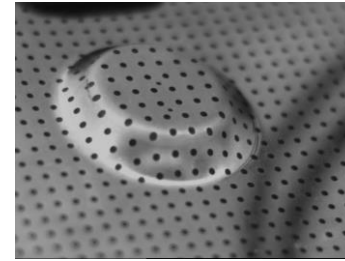
(a) Measured, (b) approximated and (c) residual (1) x and (2) y displacement fields obtained for a 45° specimen (μm).

*Novel experimental approach for longitudinal-radial stiffness
characterisation of clear wood by a single test*

J.Xavier, S.Avril, F. Pierron and J. Morais, Holzforschung,, 2007

⇒ Mesures 3D (2D $\frac{1}{2}$, surfacique)

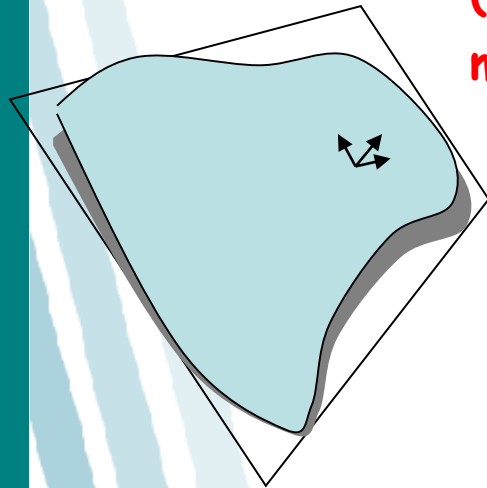
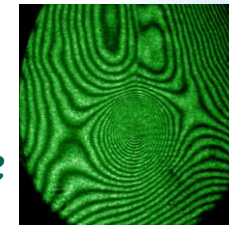
• Stéréovision
(Corrélation, suivi de marqueurs)



• Projection de lumière structurée, moiré d'ombre



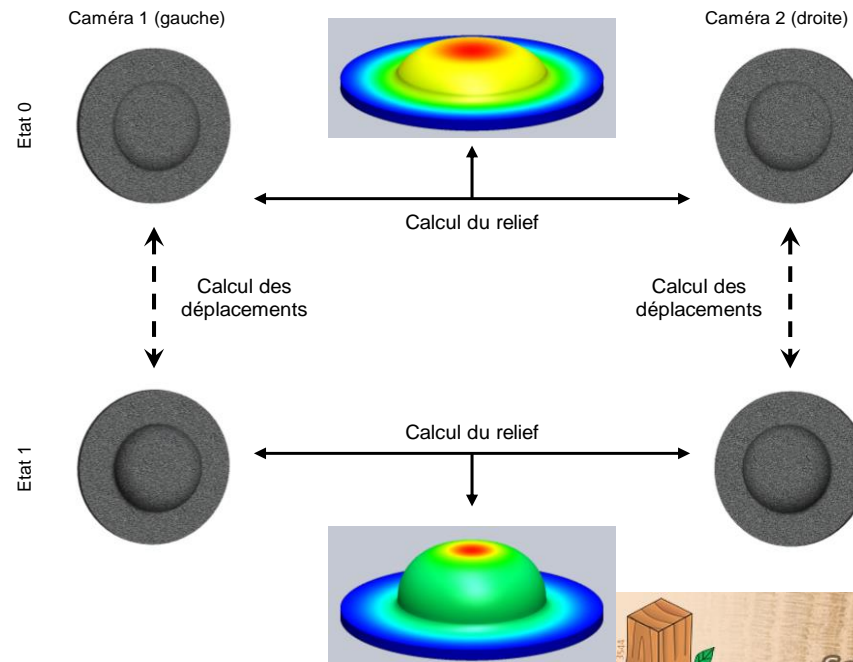
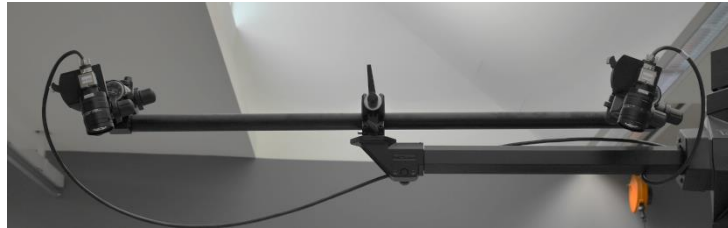
• Interférométrie, shearographie



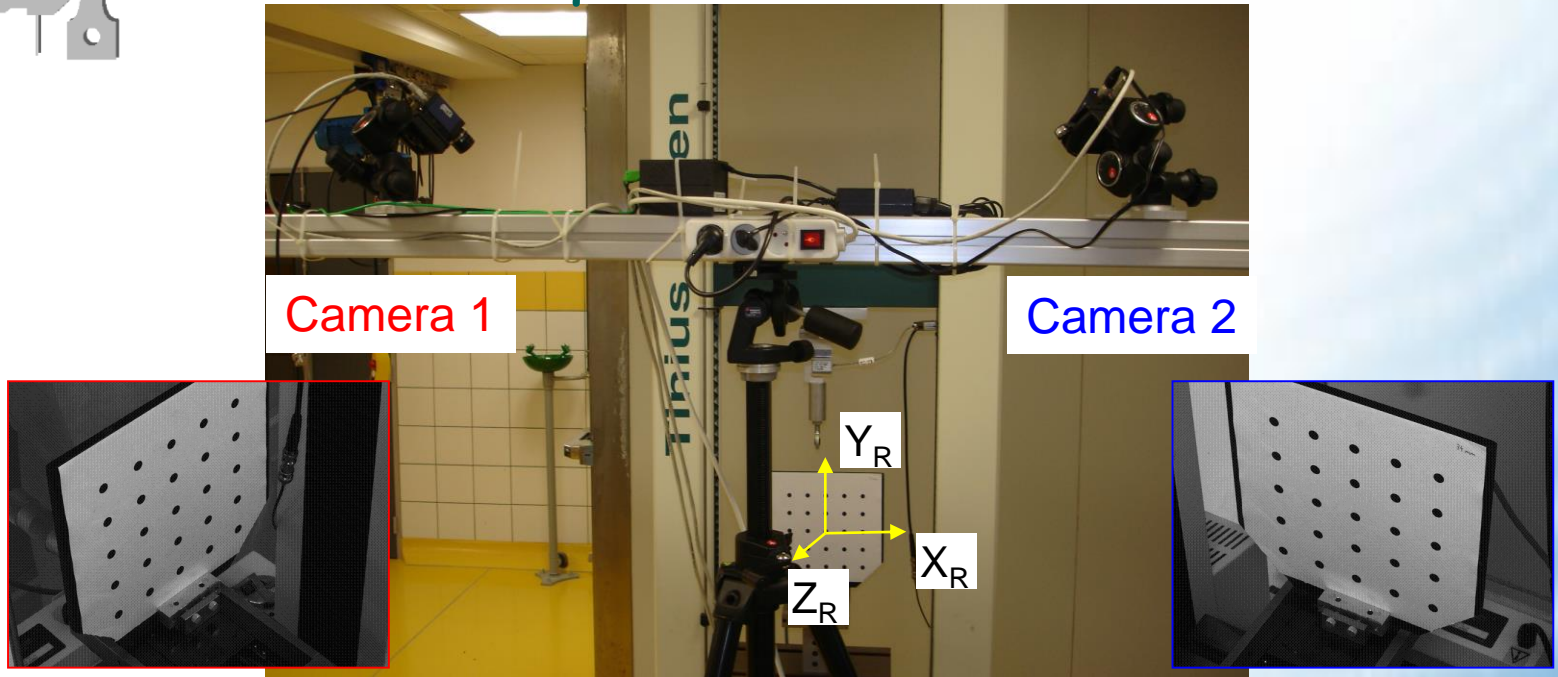
- Déplacements
- Déformations
- Relief

Stéréo-corrélation et stéréo-suivi de marqueurs

Extension à la mesure 2D au cas 2D $\frac{1}{2}$ par stéréo-vision: stéréo corrélation ou stéréo suivi de marqueurs



Stéréo-corrélation et stéréo-suivi de marqueurs



- 1) Calculation of the coordinates of marks for each camera

$$\underline{X}_1 = (x_{C1}, y_{C1}, 0)$$

$$\underline{X}_2 = (x_{C2}, y_{C2}, 0)$$

- 2) Calculation of the 3D coordinates of marks $\underline{X}_R = (x_R, y_R, z_R)$ by solving the system

Rotation matrix
(angular positions)

$$\left. \begin{array}{l} \underline{R}_1 \underline{X}_R = \underline{G}_1 \underline{X}_{C1} \\ \underline{R}_2 \underline{X}_R = \underline{G}_2 \underline{X}_{C2} \end{array} \right\}$$

Transformation vector
(magnification, positions)



Calibration process



Performances:

Calcul des déplacements en surface (x,y,z)

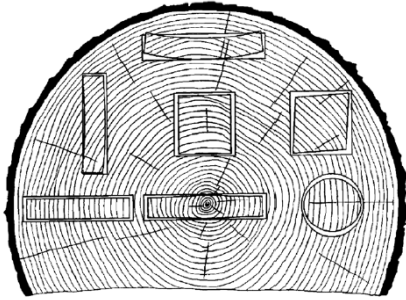
+ Mêmes performances qu'en 2D

 Attention plus sensible aux distorsions, aux imperfections du montage, à l'étalonnage



Stéréo corrélation / Suivi de marqueurs

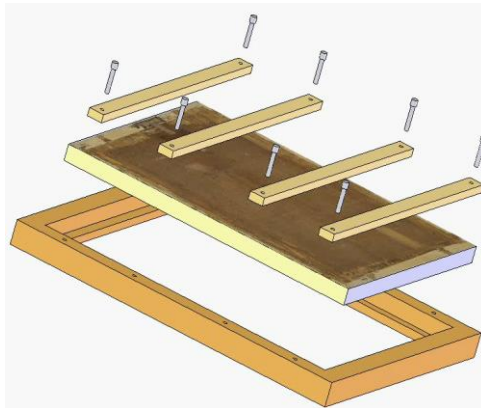
⇒ différentes applications



Chargements hygroscopique,
thermique, mécanique... (couplés)
Avec face isolée... échelle macro,
meso, micro



Etude de l'arbre sur pied



Panneau peint, effet mécanique du
cadre, d'une restauration...



Comportement mécanique
de matériaux fibreux

Mesure de déformation par stéréocorrélation:

Identification (module d'Young)

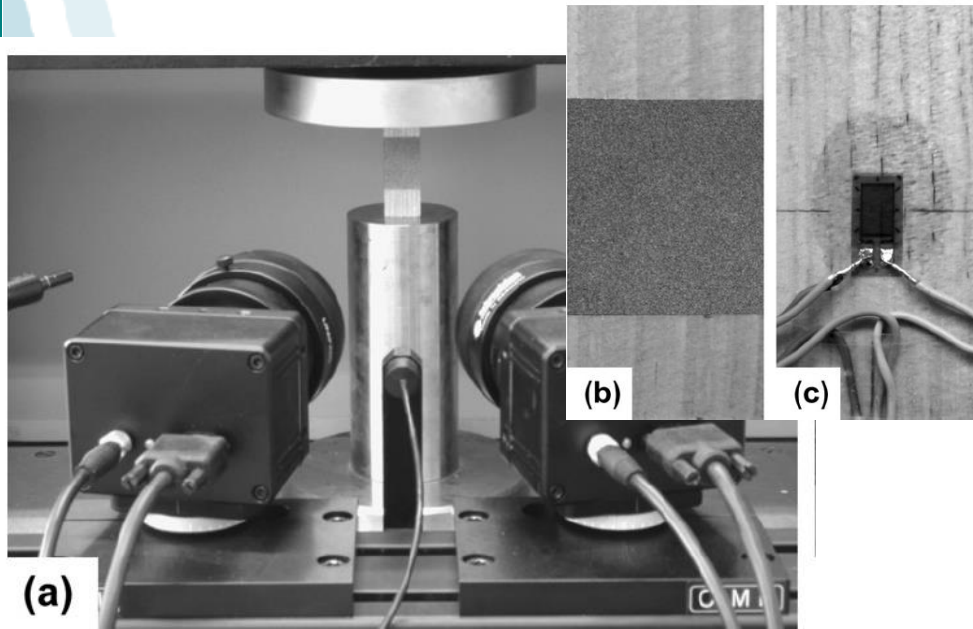


Fig. 3. Photomechanical set-up and specimen instrumentation: (a) stereovision set-up, (b) speckle pattern, and (c) strain gauge.

Stereovision measurements on evaluating the modulus of elasticity of wood by compression tests parallel to the grain
 By: Xavier, J.; de Jesus, A. M. P.; Morais, J. J. L. et al.,
 CONSTRUCTION AND BUILDING MATERIALS, V: 26, 2012

Mesure par suivi de marqueurs

PanneauGesso

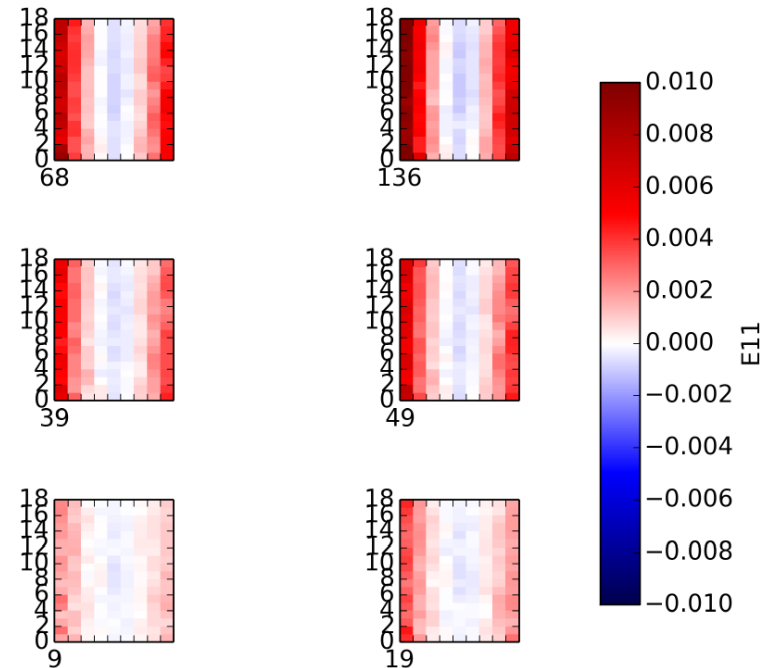


FIGURE 3.28 – Déformation horizontale d'une planche de peuplier isolée sur les faces latérales et recouverte d'une couche préparatoire, lors d'un séchage entre 60 et 40% HR, 20° C.

Cécilia Gauvin (thèse Univ. Montpellier 2015)

Etude hygromécanique d'un panneau peint :

Mesure de forme par stéro-corrélation:

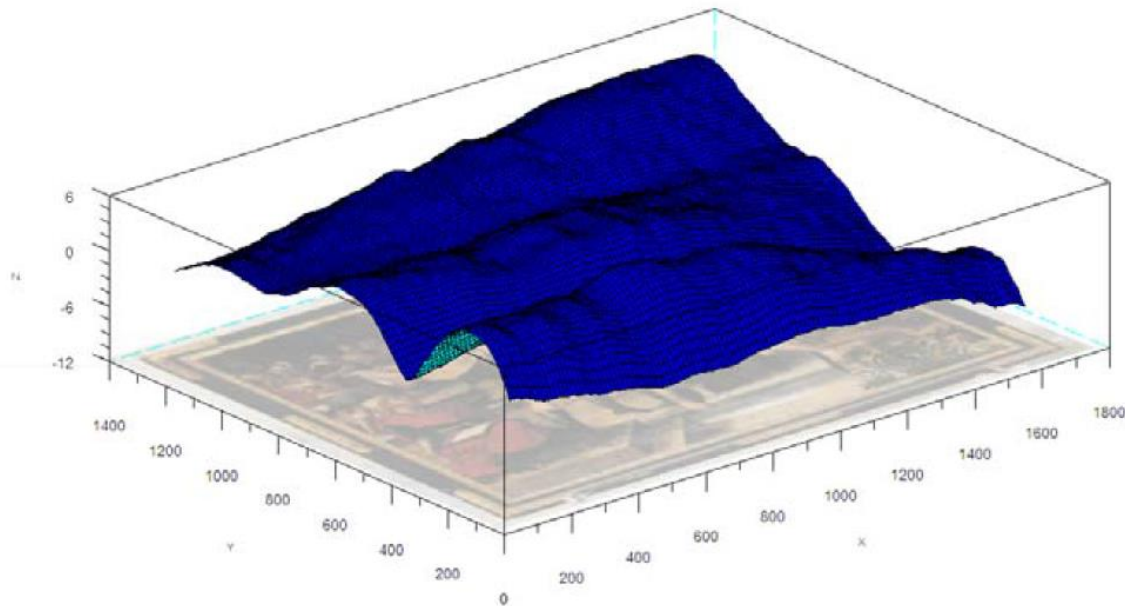
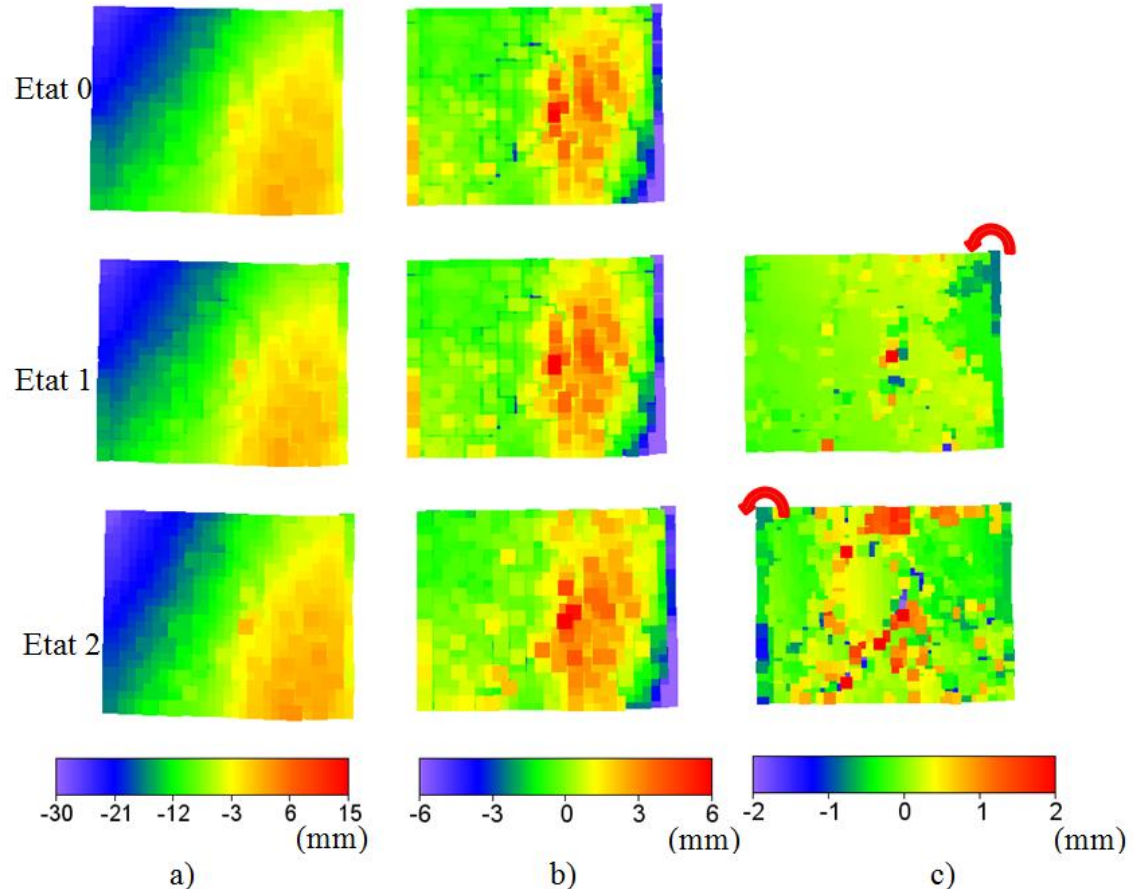


Figure 1 :
Length:

n, France).
osition

J. Colmars, B. Marcon, E. Maurin, R. Remond, F. Morestin, et al.. Hygromechanical response of a panel painting in a church, monitoring and computer modeling. International conference on wooden cultural heritage, Evaluation of deterioration and management of change, Oct 2009, Germany. 9p., 2009.

Etude hyg peint : Mesure de f

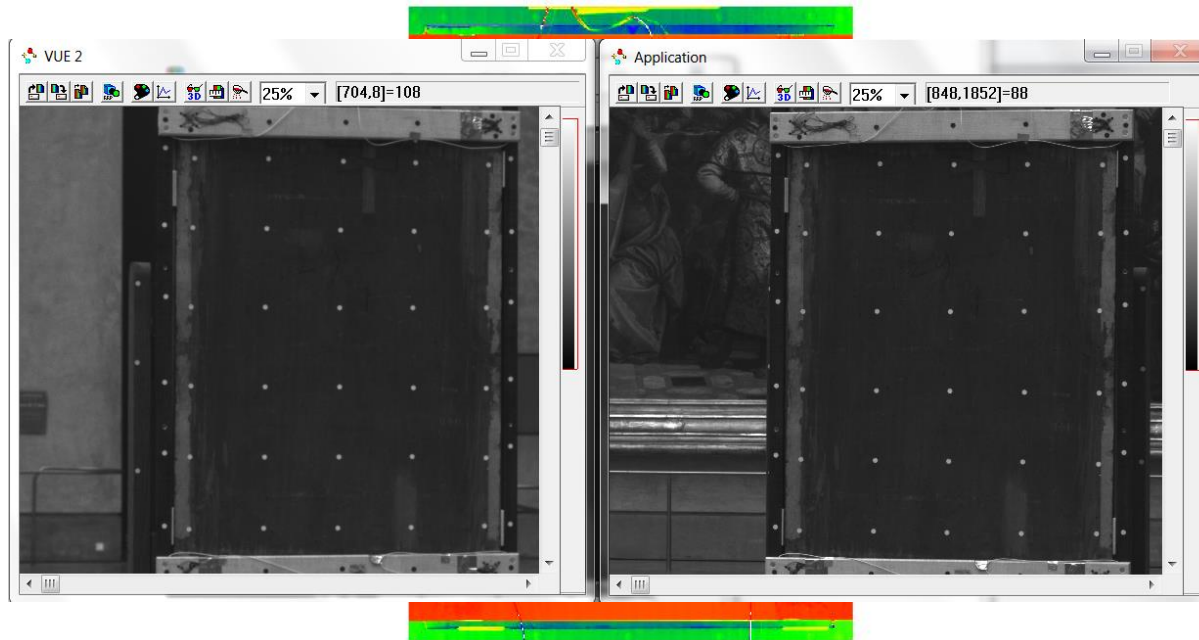


 **Précision**

Figure 15 : résultat obtenu par stéréo-corrélation après vissage-dévisage des traverses : a) relief mesuré, b) relief recalé, c) déformée obtenue

Etude hygromécanique et mécanique d'un panneau peint :
Effet du dévissage des travées

Mesure de relief et de déformée **Mesure de la déformation horizontale**

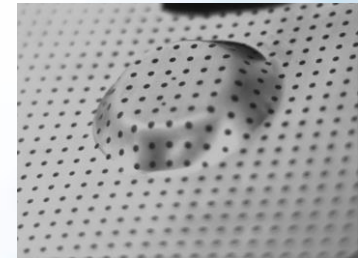
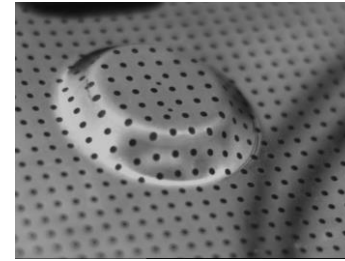


 **Données ciblées**

J.C. Dupré, F. Brémand, P. Doumalin, A. Germaneau, F. Hesser and V. Valle, "Painting panel analysis by optical methods, Digital Image Correlation, mark tracking technique and Fringe Pattern Profilometry"; GDR 3544 COST FP1302 WoodMusICK, Wood aging resulting from hygrothermal actions, Montpellier, 2015

⇒ Mesures 3D (2D $\frac{1}{2}$, surfacique)

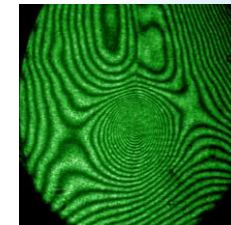
• Stéréovision
(Corrélation, suivi de marqueurs)



• Projection de lumière structurée, moiré d'ombre



• Interférométrie, shearographie



- Déplacements
- Déformations
- Relief

Principle:

Projection of lines on the specimen

Fringes analysis:

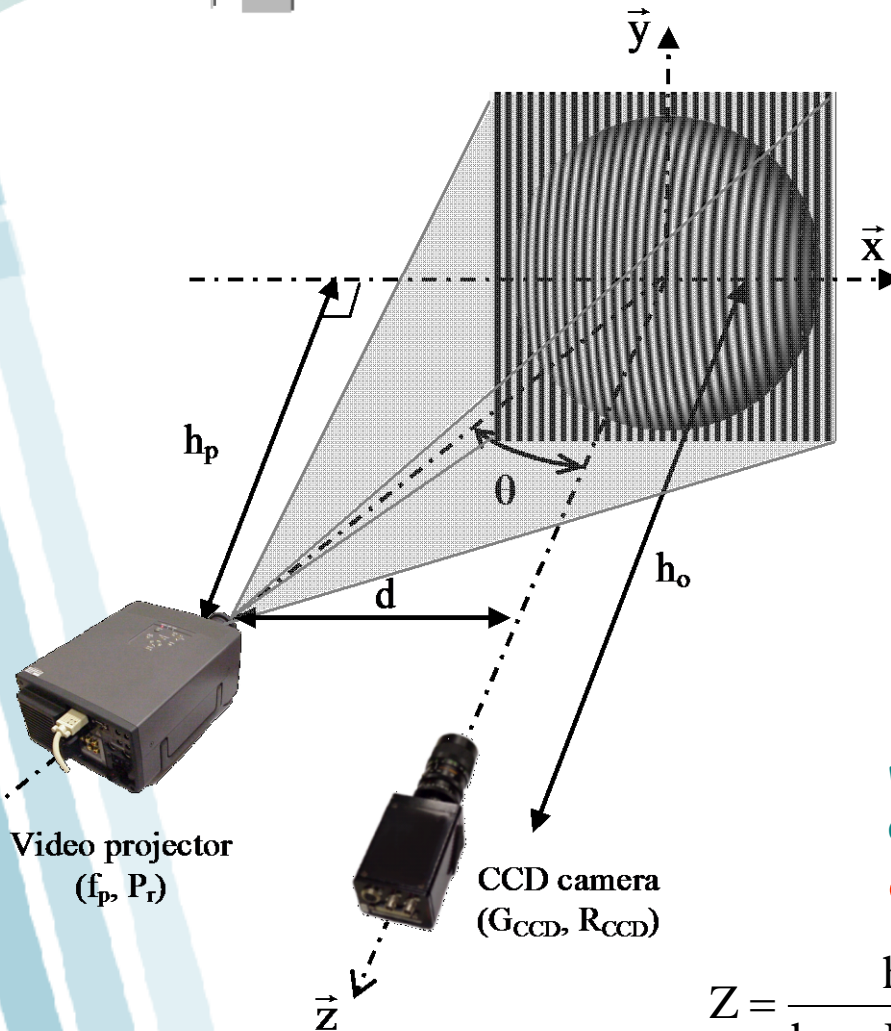
the light intensity (I) recorded by the CCD camera can be expressed, at each pixel (i, j), by

$$I(i, j) = I_0(i, j) + I_1(i, j) \sin(\varphi(i, j))$$

with I_0 as the background and I_1 as the amplitude of the fringe pattern

φ is function to the relief

$$Z = \frac{h_o \cdot (C_x \cdot d \cdot \varphi \cdot P_r - 2\pi \cdot C_x \cdot h_p \cdot f_p + l_p^2 \cdot \varphi \cdot P_r)}{h_p \cdot \varphi \cdot P_r \cdot h_o + 2\pi \cdot d \cdot f_p \cdot h_o + C_x \cdot d \cdot \varphi \cdot P_r - 2\pi \cdot C_x \cdot h_p \cdot f_p}$$



**Performances:**

+ sans contact, pas de **préparation de la surface**

+ mesure **plein champ**

- Mesure du relief,
pas de mesure de déplacement dans les directions x,y

🔔 Précision fonction du **contraste local**
(couleur, brillance)

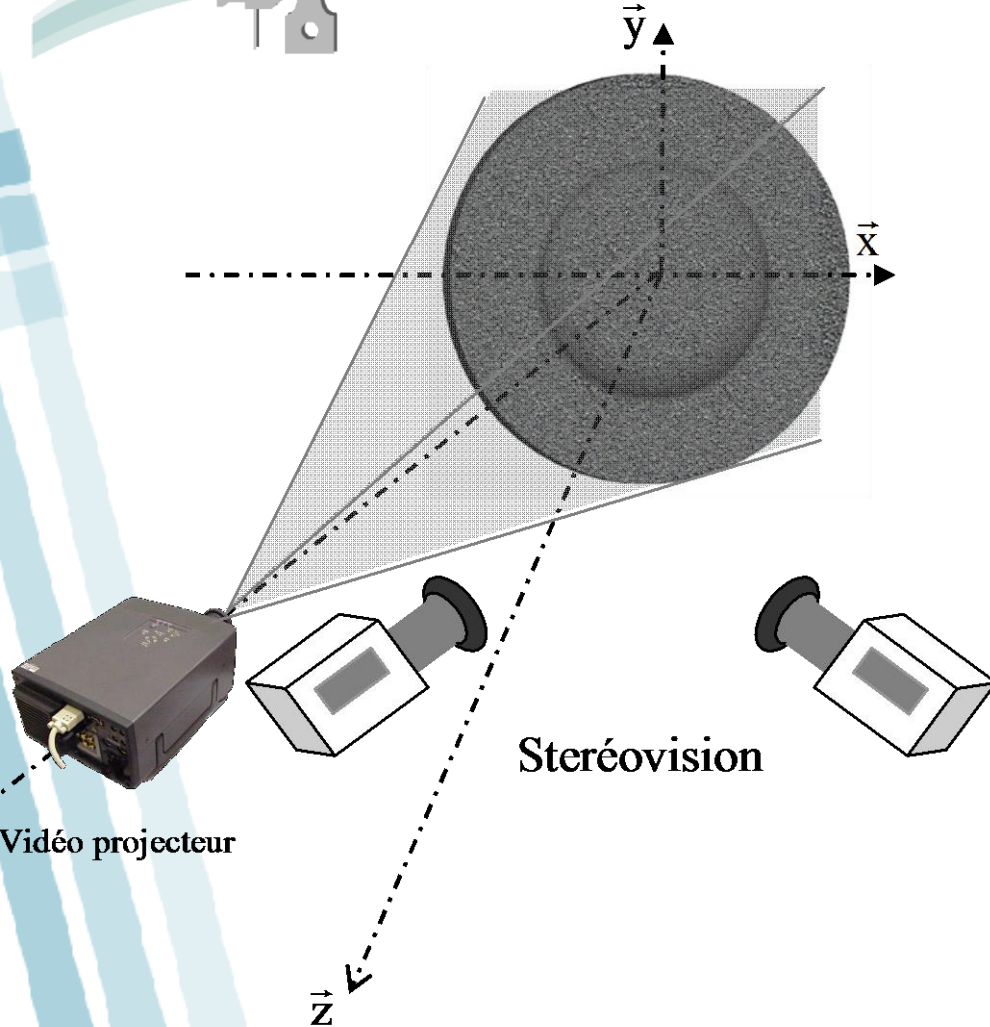
Incertitude = 1/300 fringe
(for a specimen size: $1000 \times 1000 \text{mm}^2$: 4/100 mm)

Résolution spatiale fonction de la résolution de la camera

F. Brémand, et al, "Optical techniques for Relief study of Mona Lisa'S Wooden support", Proceedings of the 13th International Conference on Experimental Mechanics Gdoutos Editor Springer, Alexandroupolis, Greece, July 1-6, 2007.



Projection de mouchetis



Principe:

Projection de **mouchetis** et
procédure de
stéréocorrélation

Intensité lumineuse
projetée **modulée** en
fonction du contraste de la
surface



Projection de mouchetis

Performances:

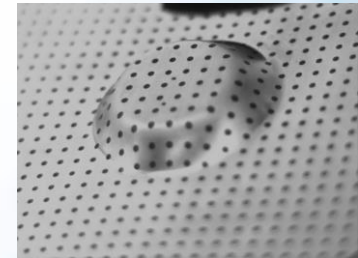
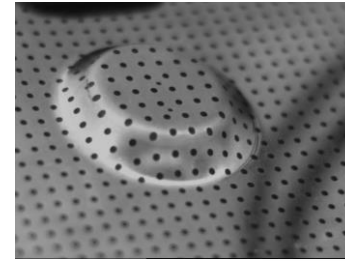
- + sans contact, pas de **préparation de la surface**
- + **utilisation** d'algorithme de **stéréocorrélation**
- Mesure du relief, **pas de mesure de déplacement** dans les directions x,y
- 🔔 Précision fonction du **contraste local** (procédure de compensation)

Incertitude fonction des fenêtres de corrélation et du montage

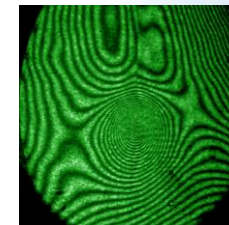
Base de mesure fonction des fenêtres de corrélation

⇒ Mesures 3D (2D $\frac{1}{2}$, surfacique)

• Stéréovision
(Corrélation, suivi de marqueurs)



• Projection de lumière structurée, moiré d'ombre



- Déplacements
- Déformations
- Relief

• Interférométrie, shearographie

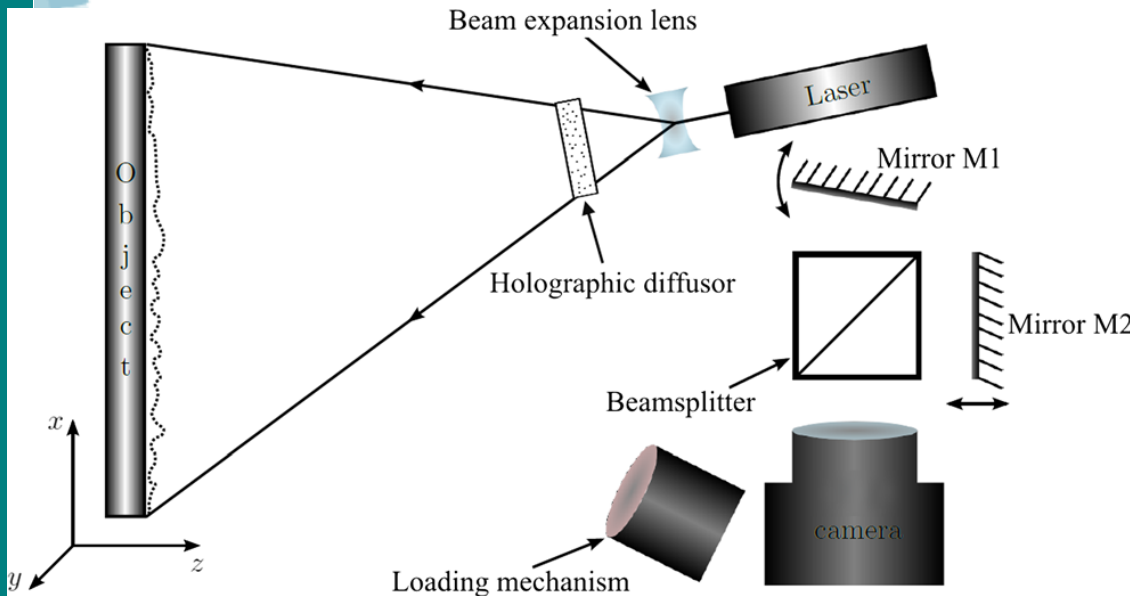
Principe:

Interférométrie

+ référence au niveau de la visualisation

+ (-) grande sensibilité

+ Etude de défauts locaux



Detection of transport and age induced damages on artwork: an advanced concept

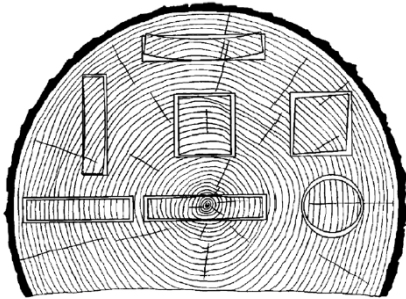
By: Morawitz, M.; Hein, N.; Alexeenko, I.; et al.

Edited by: Pezzati, L; Targowski, P, Conference on Optics for Arts, Architecture, and Archaeology IV , Munich, GERMANY, MAY 15-16, 2013, SPIE



Projection de traits / mouchetis

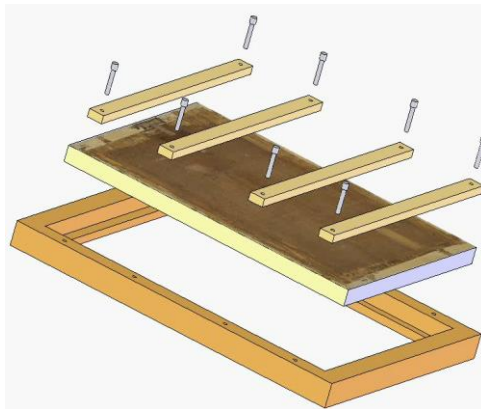
⇒ différentes applications



Chargements hygroscopique,
thermique, mécanique... (couplés)
Avec face isolée... échelle macro,
meso, micro



Etude de l'arbre sur pied



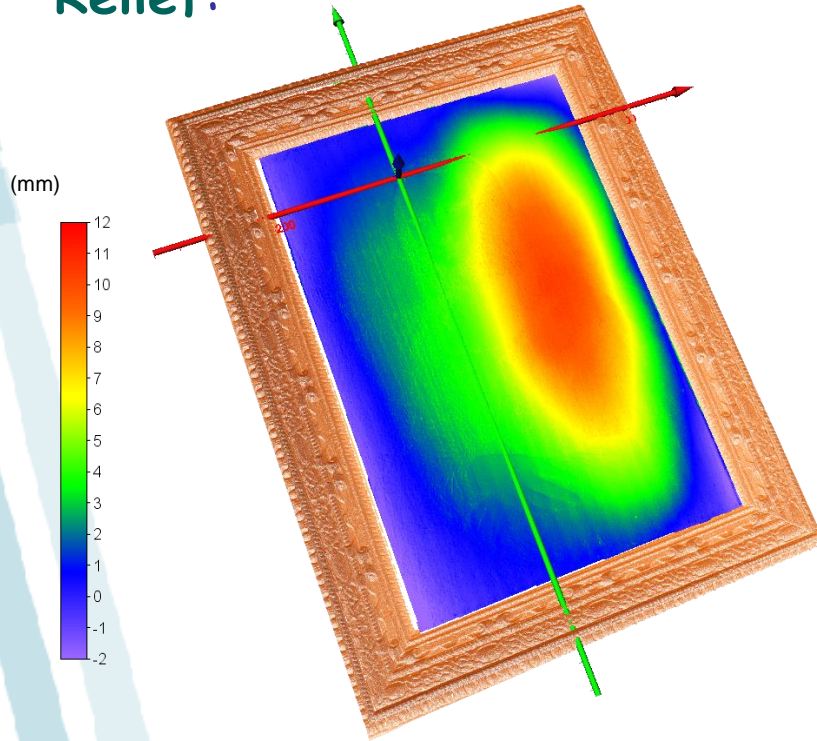
Panneau peint, effet mécanique du
cadre, d'une restauration...



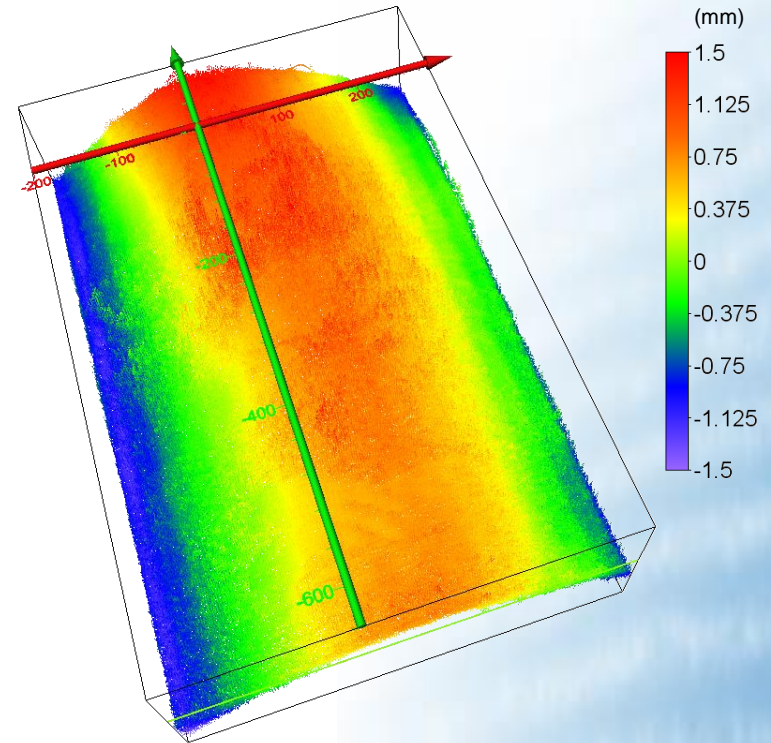
Comportement mécanique
de matériaux fibreux



Relief:

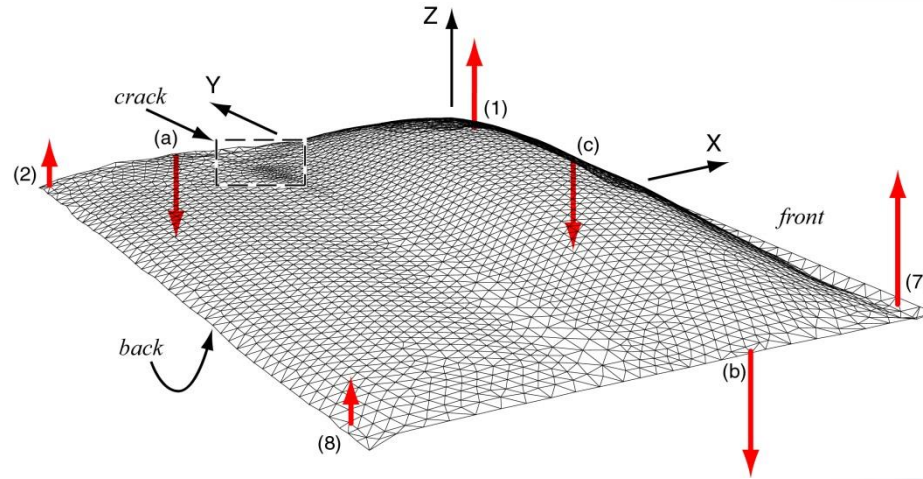


Déformée due au cadre:

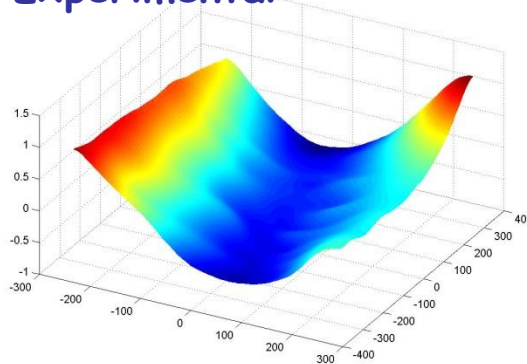


Accuracy: $\Delta z = 3/100 \text{ mm}$
 Strain gauge = 0.4 mm/pixel

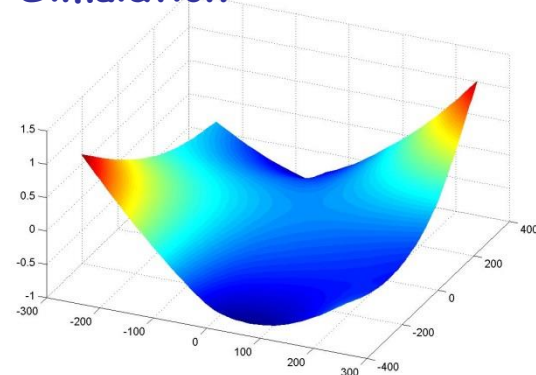
F. Brémand, et al, "Optical techniques for Relief study of Mona Lisa'S Wooden support", Proceedings of the 13th International Conference on Experimental Mechanics Gdoutos Editor Springer, Alexandroupolis, Greece, July 1-6, 2007.



➔ Experimental :



Simulation :



Gril J., et al., "Mona Lisa saved by Griffith theory: assessing the crack propagation risk in the wooden support of a panel painting", Integrated Approach to Wood Structure, Behaviour and Applications ESWM and COST Action E35 meeting; Florence (Italy), 14-17 mai 2006



Effet du **changement** des travées étude expérimentale et simulation numérique (détermination des contraintes)

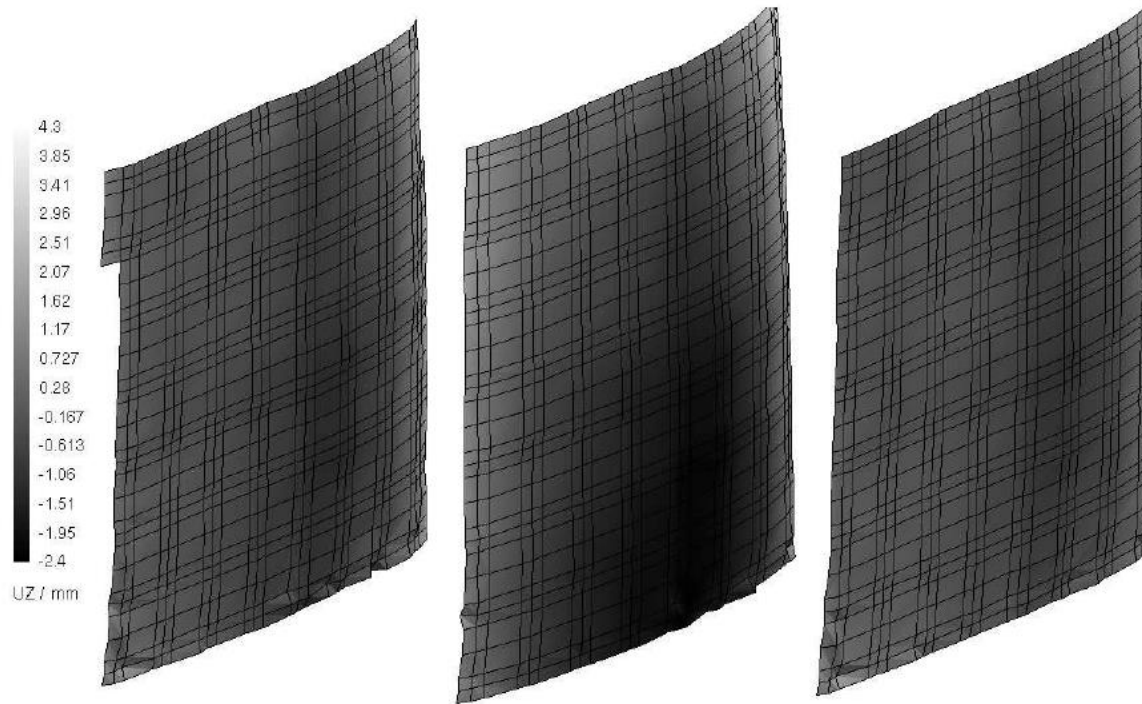


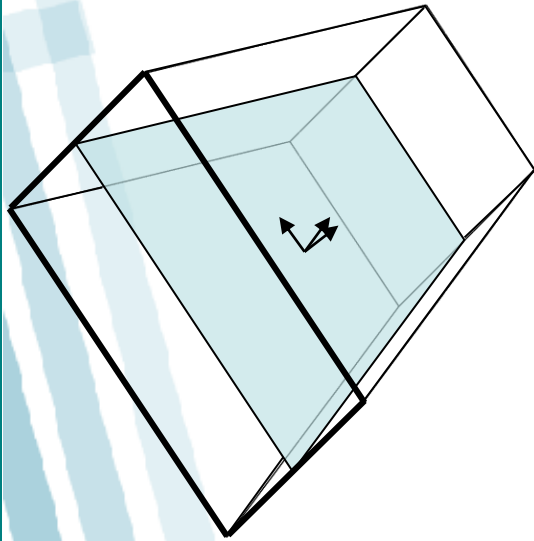
Figure 8: Measured fields projected onto the finite element mesh: initial state (left), after beam removal (middle), and after beam replacement (right). Displacement amplified 8 times.



➔ • Mesures 3D (volumique)

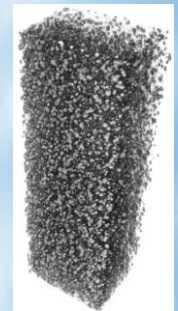
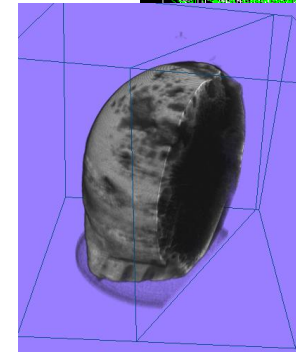
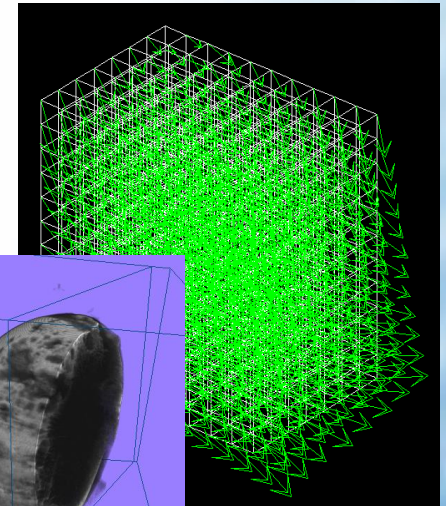
• Corrélation d'images volumiques

$$(u(x, y, z), v(x, y, z), w(x, y, z))$$



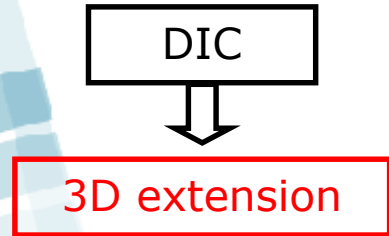
- Déplacements
- Déformations
- (Contraintes)

- μ Tomographie RX
- IRM
- Tomographie optique
- Microscopie confocale

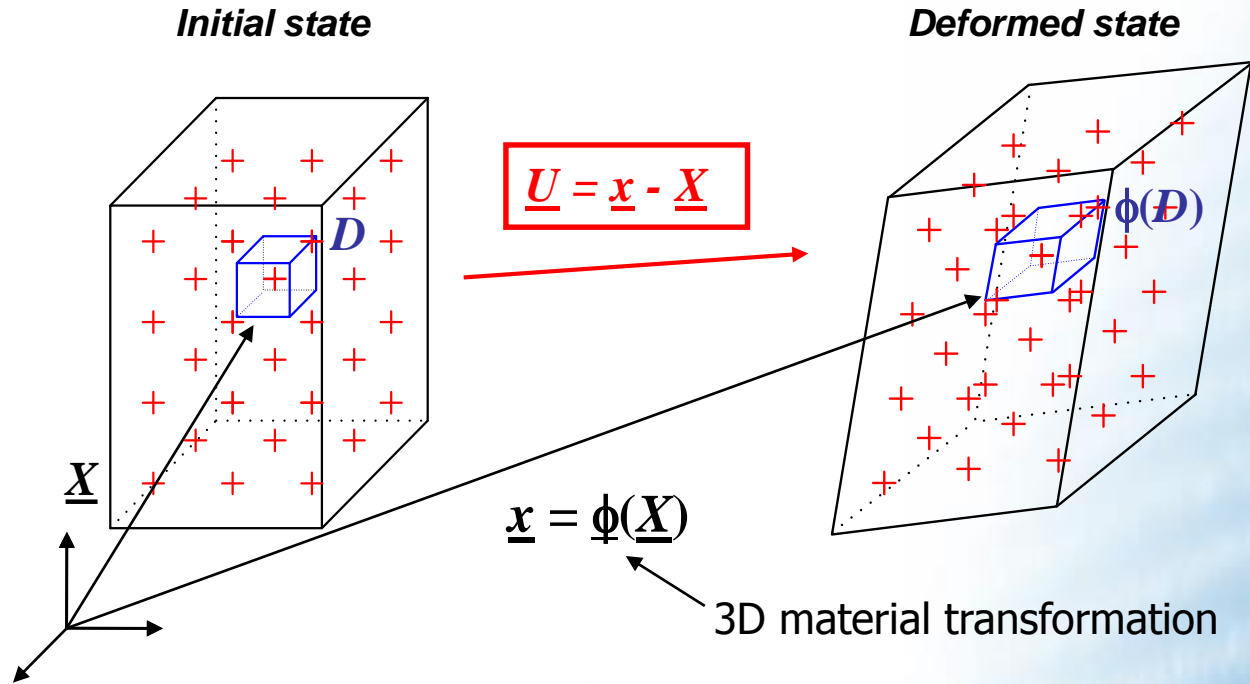




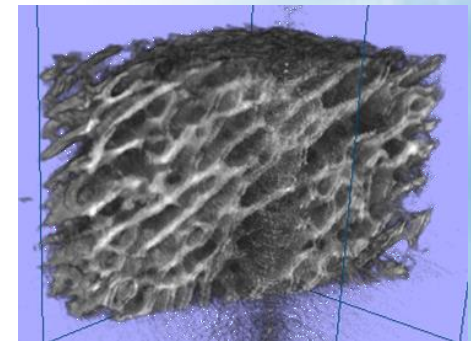
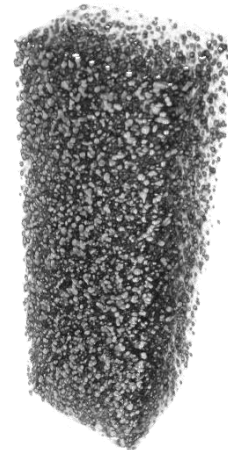
Digital Volume correlation (DVC)



Volume images:
3D distribution of
grey levels



Contraste naturel
ou artificiel



Germaneau A, et al Comparison between X-ray micro-computed tomography and optical scanning tomography for full 3D strain measurement by digital volume correlation. NDT&E. 2008.

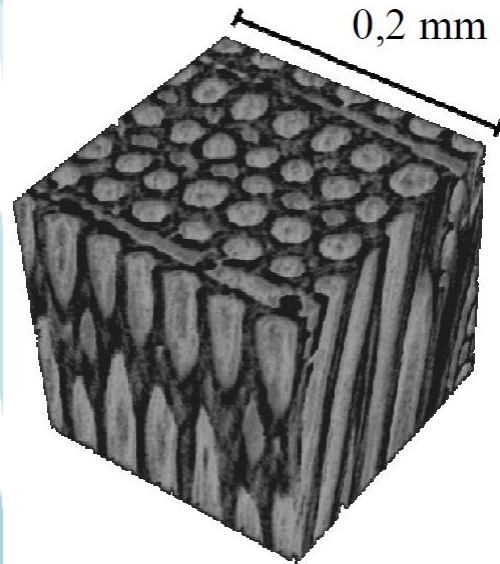


Utilisation de la **microstructure**

pour obtenir un contraste naturel

⇒ Couplage principalement avec la **µtomo RX labo et Synchrotron**

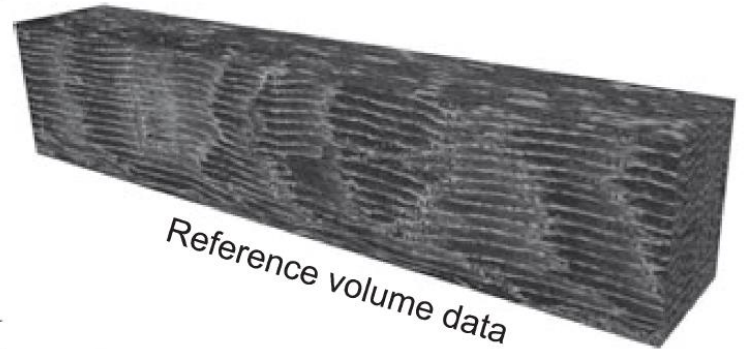
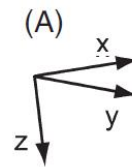
Pin Douglas



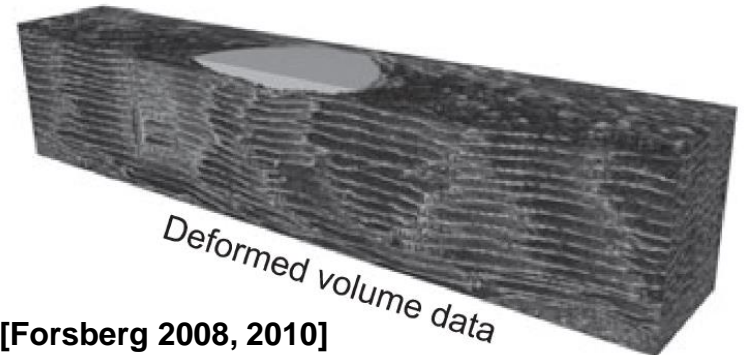
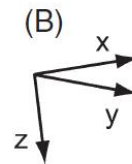
Bois massif

Pin Sylvestre

1,57x3,42x0,75mm³

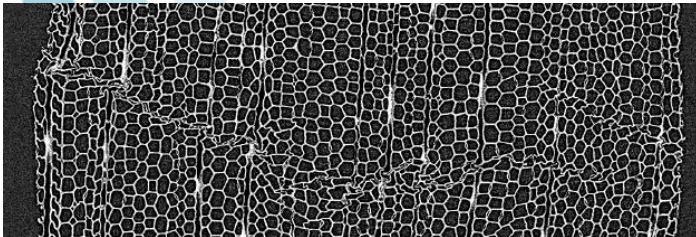


Reference volume data



Deformed volume data

[Forsberg 2008, 2010]



[Bonnet 2015]

Utilisation de la **microstructure**

pour obtenir un contraste naturel

Panneau isolant fibres

bois/PES

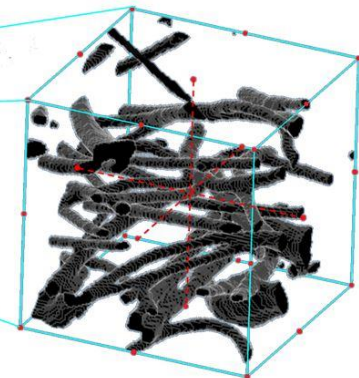
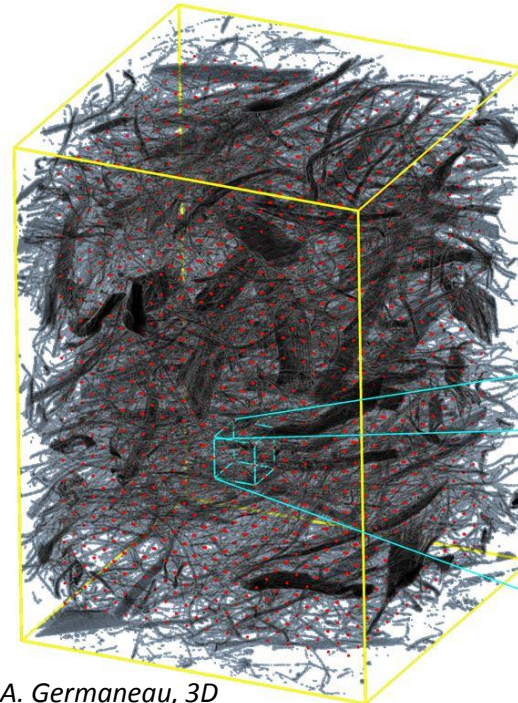
Pin maritime

Mats de fibres cellulose

Fibres de bois

5,4x5,4x7,56mm²

(a)

4x4x2,2mm³

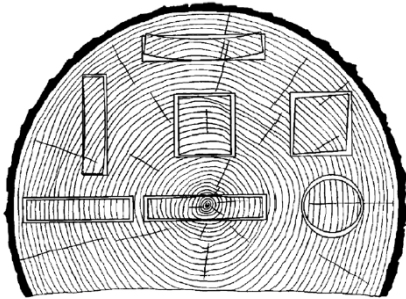
T. Joffre, O. Girlanda, F. Forsberg, F. Sahlen, M. Sjö Dahl, E.K. Gamstedt, A 3D in-situ investigation of the deformation in compressive loading in the thickness direction of cellulose fiber mats, *Cellulose*, Vol. 22, No. 5, 2015

H. Tran, P. Doumalin, C. Delisée, J.C. Dupré, J. Malvesto, A. Germaneau, 3D mechanical analysis of low-density wood based fiberboards using X-ray microcomputed tomography and Digital Volume Correlation, *Journal of Materials Science*, 48, 2013



Corrélation volumique

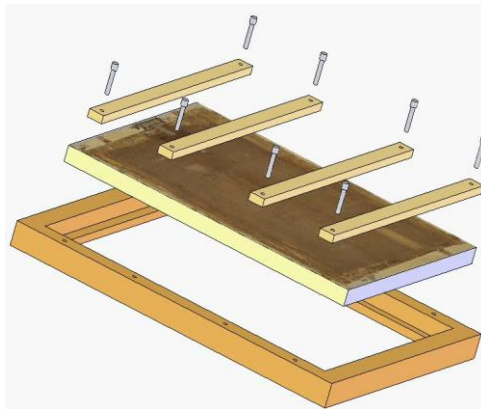
⇒ différentes applications



Chargements hygroscopique,
thermique, mécanique... (couplés)
Avec face isolée... échelle macro,
meso, micro



Etude de l'arbre sur pied



Panneau peint, effet mécanique du
cadre, d'une restauration...



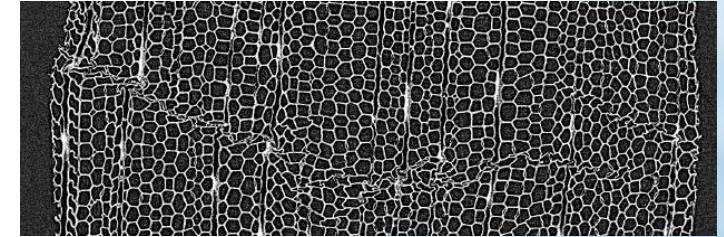
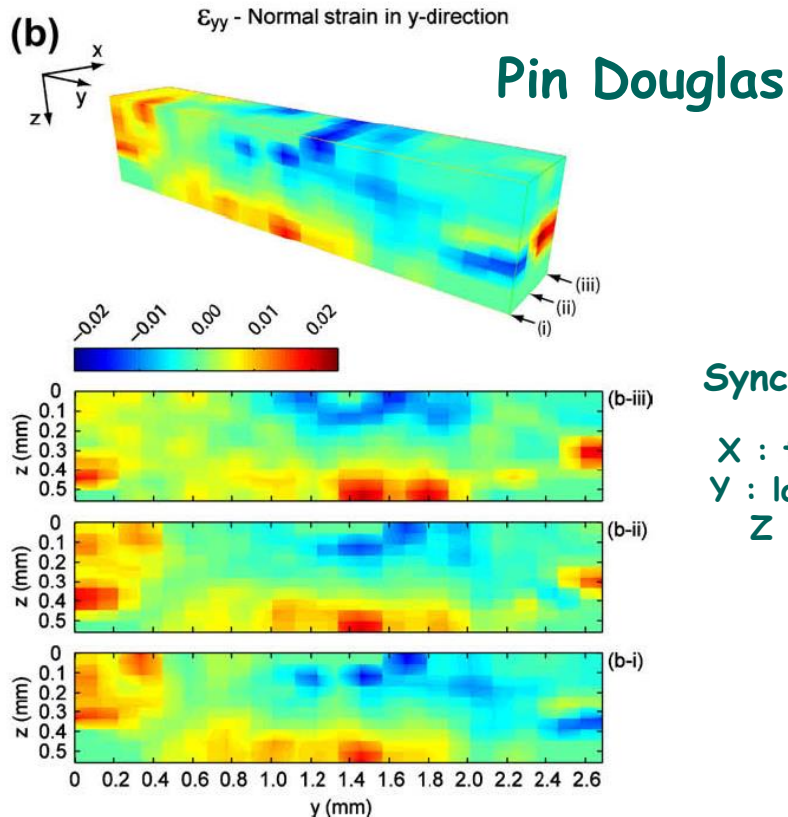
Comportement mécanique
de matériaux fibreux



Bois massif

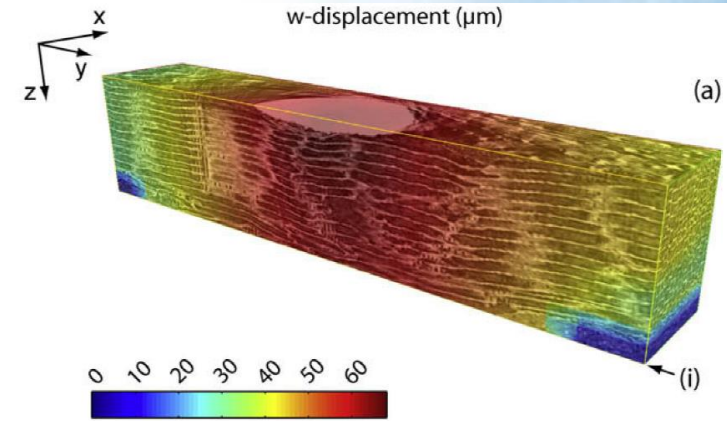
Détermination des mécanismes de déformation à l'échelle cellulaire

Compression direction radiale/Synchrotron Soleil



Bande d'écrasement cellulaire

Pin Sylvestre Flexion 3 points



M. Bonnet, S. Caré, M. Bornert, P. Aïmedieu, A. King, Essais de compression in-situ dans la direction radiale des bois de printemps et d'été observés par microtomographie aux rayons X, 4èmes journées du GDR 3544 « Sciences du bois » - Clermont-Ferrand, 2015

F. Forsberg, R. Mooser, M. Arnold, E. Hack, P. Wyss, 3D micro-scale deformations of wood in bending: Synchrotron radiation ICTdata analyzed with digital volume correlation, Journal of Structural Biology 164 (2008)

Digital Volume correlation (DVC)

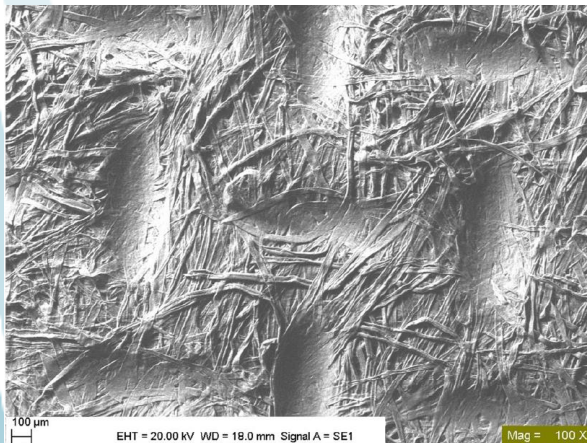
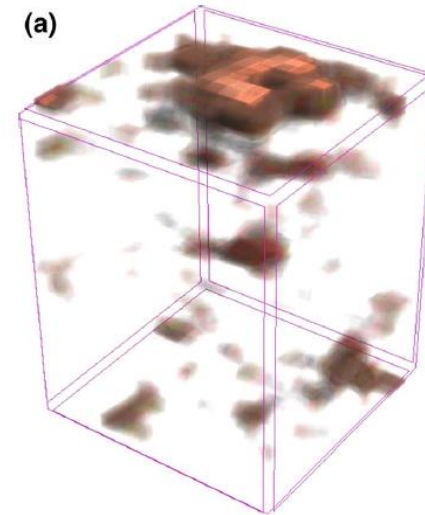
Mats de fibres cellulose Haute densité

Compression

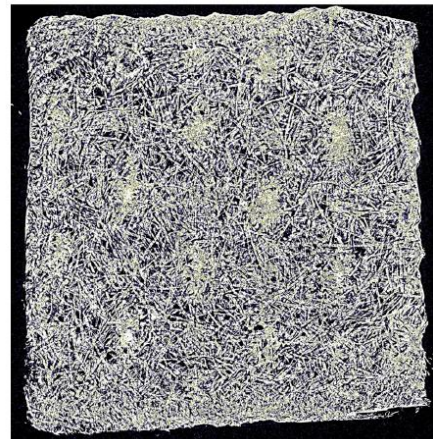
(a)



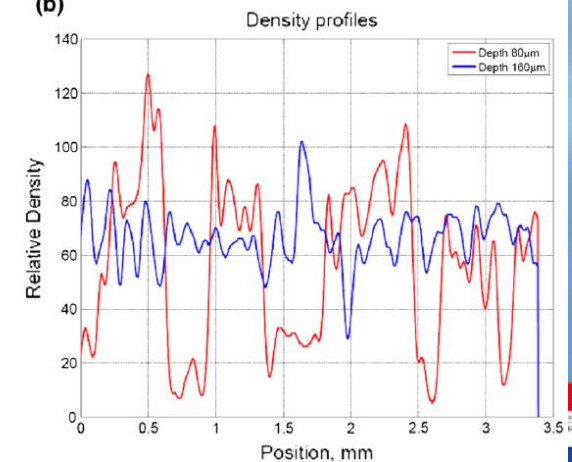
(a)

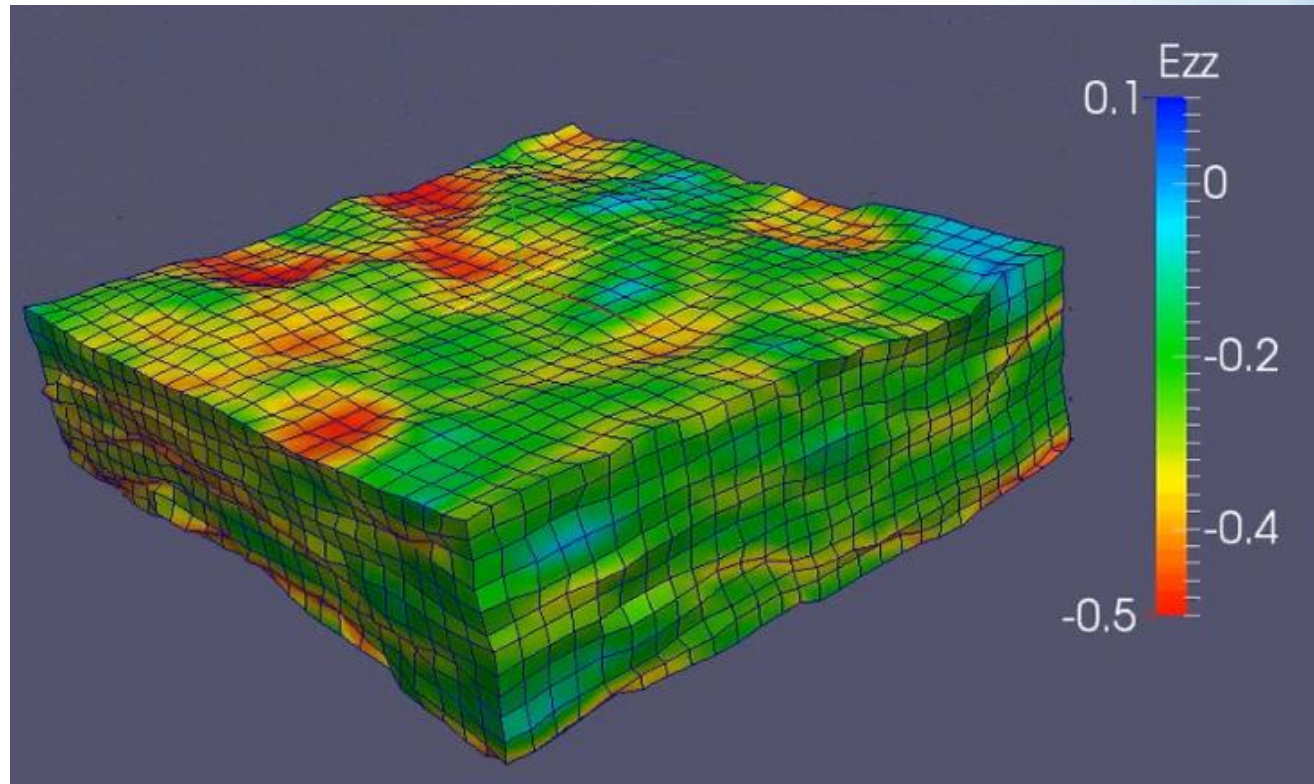


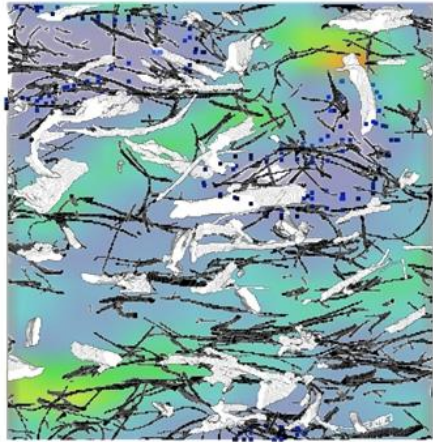
(a)



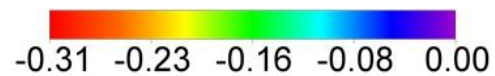
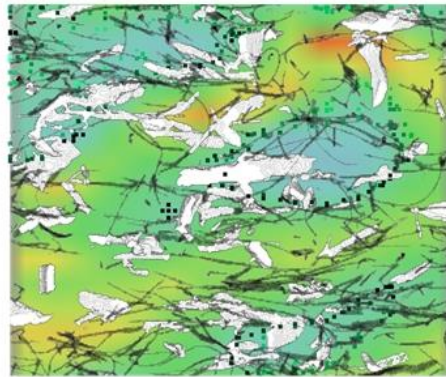
(b)



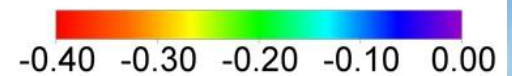
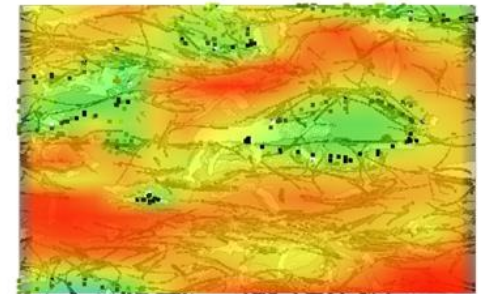
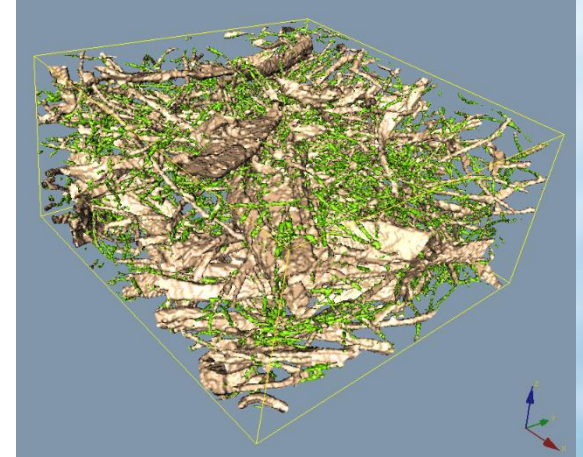


Lien μ structure-déformation

(a) State 4.9%



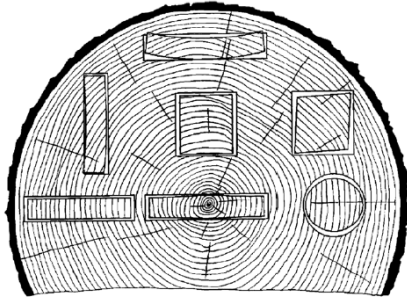
(b) State 18.4%



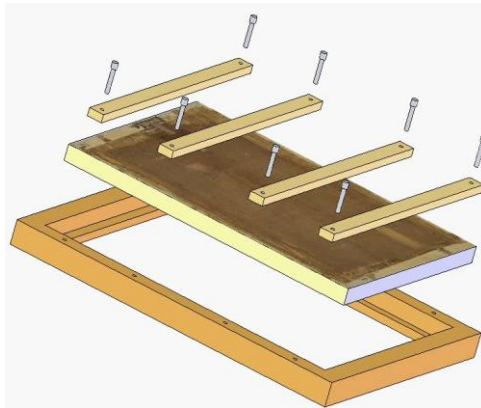
(c) State 31.6%



⇒ Pour l'étude du bois sous toutes ces formes !



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Avec face isolée... échelle macro,
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