

Effets thermo-visco-hydro-mécanique (TVHM) et couplage mécano-fiabiliste via les intégrales invariantes : application aux structures bois

<u>R. Moutou Pitti^{1,2,5}</u>, T.B. Tran³, S.E. Hamdi^{1,2}, E. Bastidas Arteagas³, C.F. Pambou Nziengui^{1,2,6}, Y. Aoues⁴, E. Fournely^{1,2}

¹Université Clermont Auvergne, UBP, IP, EA 3867, F-63000 Clermont-Fd ²CNRS, UMR 6602, Institut Pascal, 63171, Aubière, France ³Laboratoire GeM Institut de recherche en Génie Civil et Mécanique, Université de Nantes, France ⁴Normandie Univ, INSA Rouen, LOFIMS, 76000 Rouen, France ⁵CENAREST, IRT, BP 10400, Libreville, Gabon ⁶Ecole Nationale des Eaux et Forêts (ENEF), Gabon

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rostand.moutou_pitti@univ-bpclermont.fr













External loading

-Permanent loads -Service charges -Snow and wind -Traffic

Climatic conditions

- -Variations of temperature
- -Variations of relative humidity
- -Moisture content transfer

Long term behavior

- Acceleration of creep
- Shrinkage-swelling effects
- Development of hydric stresses
- Development of cracks

Scientific context

Crack



Evaluation of energy release rate in orthotropic materials under environmental effects



environmental effects

Crack propagation in civil engineering structures

Non-dependent integrals

□ Thermo-visco-hydro-mechanical (TVHM) effects

Orthotropic materials like wood

Mechanical parameter importance by reliability method



2 Generalization to viscoelastic crack growth materials

3 Numerical results and discussions

4 Coupled mechanics-reliability methodology

5 Conclusions and perspectives

Path independent integrals in orthotropic materials Domains - T and A integrals

Integration domains



Domains – T and A integrals

T and A integrals formulation

Virtual and real displacement fieds

Real fields (FEM)

$$\varepsilon_{ij}^{u} = \frac{1}{2} (u_{i,j} + u_{j,i})$$

$$\sigma_{ij}^{u} = \lambda \, \delta_{ij} u_{k,k} + \mu (u_{i,j} + u_{j,i})$$

$$T^{u} = \Delta T = T - T_{0}$$

Temperature variation

$$\Delta T = T - T_0$$

Virtual fields (auxiliary problem)

$$\varepsilon_{ij}^{\nu} = \frac{1}{2} (v_{i,j} + v_{j,i})$$

$$\sigma_{ij}^{\nu} = \lambda \, \delta_{ij} v_{k,k} + \mu (v_{i,j} + v_{j,i})$$

$$T^{\nu} = 0$$

T-integral formulation

$$T = \int_{\Gamma} \frac{1}{2} \left[\sigma_{ij,1}^{v} u_{i} - \sigma_{ij}^{u} v_{i,1} - \gamma \Delta T \left(v_{1,j} - \psi_{1,j} \right) + \gamma \Delta T_{j} (v_{1} - \psi_{1}) \right] n_{j} dl$$

A-integral formulation

$$A = T_{\theta} = \int_{V} -\frac{1}{2} \Big[\sigma_{ij,1}^{v} u_{i} - \sigma_{ij}^{u} v_{i,1} - \gamma \Delta T \big(v_{1,j} - \psi_{1,j} \big) + \gamma \Delta T_{,j} (v_{1} - \psi_{1}) \Big] \theta_{1,j} dV$$

$$A_{1}: \text{ Classical term} \qquad A_{2}: \text{ temperature variation effect}$$

Domains – T and A integrals

T and A integrals formulations in orthotropic materials



Plan stress condition

Temperature variation

1

ε ₁₁		$\int 1/E_1$	$-v_{12}/E_1$	ך 0	$\left\lceil \sigma_{11} \right\rceil$	$\begin{bmatrix} \alpha_1 \Delta T \end{bmatrix}$
E22	=	$-v_{12}/E_1$	$1/E_2$	0	σ_{22}	$+ \alpha_2 \Delta T$
2ε ₁₂		0	0	$1/G_{12}$	σ_{12}	[0 /]

Elastic parameters

Parameters	Values
Longitudinal modulus E_1	15000 MPa
Transverse modulus E_2	600 MPa
Normal modulus E_3	600 MPa
Shear modulus G_{12}	700 MPa
Poisson's coefficient v_{12}	0.4
Poisson's coefficient v_{23}	0.4
Poisson's coefficient v_{13}	0.4

A integral in static case

$$A = T_{\theta} = \int_{V} -\frac{1}{2} \left[\sigma_{ij,1}^{\nu} u_{i} - \sigma_{ij}^{u} v_{i,1} - (\gamma \Delta T (v_{1,j} - \psi_{1,j}) + \gamma \Delta T_{,j} (v_{1} - \psi_{1}) \right] \theta_{1,j} dV$$

$$A_{1}: \text{ Classical term} \qquad A_{2}: \text{ temperature variation effect}$$



Improvement of the A-integral formulation



Ω

Applied forces on the crack lips

$$\vec{T} = \begin{cases} p(x_1) \\ q(x_1) \end{cases}$$

A-integral formulation in crack growth process

$$A = T_{\theta} = \int_{V_{\underline{i}}} -\frac{1}{2} \begin{bmatrix} \sigma_{ij,1}^{v} u_{i} - \sigma_{ij}^{u} v_{i,1} - \gamma \Delta T (v_{1,j} - \psi_{1,j}) + \gamma \Delta T_{,j} (v_{1} - \psi_{1}) \end{bmatrix} \theta_{1,j} dV$$

$$A_{1}: \text{ Classical term}$$

$$A_{2}: \text{ temperature variation effect}$$

$$-\int_{A_{1}A_{2}+B_{2}B_{1}} T_{i} v_{i,j} \theta_{j} dx_{1} - \int_{V_{\underline{i}}} \begin{bmatrix} \sigma_{ij,k}^{v} u_{i,j} + \sigma_{ij,k}^{u} v_{i,j} + \beta \delta_{ij} u_{i,jk} \Delta T \end{bmatrix} \theta_{k} dV$$

$$A_{3}: \text{ pressure applied on the crack lips}$$

$$A_{4}: \text{ effect of crack growth}$$

Creep test /Viscoelastic integral formulations in crack growth

Creep function and BOLTZMANN integral's



A integral generalized to viscoelastic crack growth materials, m = p

$$A^{m} = \int_{\Omega} \frac{1}{2} \Big[{}^{(m)} \sigma_{ij,k}^{v} u_{i}^{(m)} - {}^{(m)} \sigma_{ij}^{u} v_{i,k}^{(m)} \Big] \theta_{k,j} dS - \int_{\Omega} \frac{1}{2} \Big[\gamma \vartheta_{i} \delta_{ij} u_{i,jk}^{(m)} \Delta T_{,j} \Big] \theta_{k,j} dS$$
$$- \frac{1}{2} \int_{\Omega} \Big[{}^{(m)} \sigma_{ij,k}^{v} u_{i,j}^{(m)} + {}^{(m)} \sigma_{ij,k}^{u} v_{i,j}^{(m)} + {}^{(\beta)} \delta_{ij} u_{i,jk}^{(m)} \Delta T \Big] \theta_{k} dS$$
$$Hyp2: \beta = g(E_{1}, v_{12}, \alpha_{1}) \qquad 11$$

Analytical formulation – Energy release rate – Creep function

Physical interpretation in Viscoelastic case

Real stress intensity factor

Viscoelastic energy release rate, m=p

$${}^{1}G\theta_{v}^{(p)} + {}^{2}G\theta_{v}^{(p)} = C_{1}^{(p)} \cdot \frac{\left({}^{u}K_{I}^{(p)}\right)^{2}}{8} + C_{2}^{(p)} \cdot \frac{\left({}^{u}K_{II}^{(p)}\right)^{2}}{8}$$

with
$${}^{1}G_{v} = \sum_{p} {}^{1}G\theta_{v}^{(p)} \text{ and } {}^{2}G_{v} = \sum_{p} {}^{2}G\theta_{v}^{(p)} \quad p = m \in \{0, 1, \dots, N\}$$

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Analytical form. - Energy release rate - Incremental formulation

Strain incremental formulation / Creep function

Incremental strain tensor

$$\Delta \varepsilon_{ij}(t_{n+1}) = \Psi_{ijkl} \cdot \Delta \sigma_{kl}(t_{n+1}) + \tilde{\varepsilon}_{ij}(t_n)$$
 Strain history

Balance equation

$$\begin{pmatrix} K_T^p \\ K_T \end{pmatrix} \left\{ \Delta u^p \right\} (t_n) = \left\{ \Delta F_{ext}^p \right\} (t_n) + \left\{ \tilde{F}^p \right\} (t_{n-1})$$

Apparent Tangent matrix Supplementary viscous load vector

Creep function

$$J(t) = \frac{1}{E(t)} \cdot C_0 \quad \text{with} \quad C_0 = \begin{bmatrix} 1 & -\upsilon & 0 \\ -\upsilon & E_X / E_Y & 0 \\ 0 & 0 & E_X / G_{XY} \end{bmatrix}$$
$$\frac{1}{E(t)} = \frac{1}{E_X} \begin{bmatrix} 1 + \frac{1}{74.3} (1 - e^{-\frac{74.3}{3.37}t}) + \frac{1}{74.4} (1 - e^{-\frac{74.4}{33.37}t}) \end{bmatrix}$$



Crack growth viscoelastic simplified routine





Numerical MMCG mesh with TH variations



Routine. – MMCG and Numerical meshes – Energy realise rate

 G_I in opening mode versus time under moisture content



Evolution of G_I versus crack a for β =45°

Routine. – MMCG and Numerical meshes – Energy realise rate

 G_{II} in opening mode versus time under moisture content



Evolution of G_1 versus crack a for β =45°



Routine. - MMCG and Numerical meshes - Energy realise rate

G in mixed mode versus time under moisture content and T°



Effect of T on G_I in mixed mode $\beta = 45^{\circ}$ for variours MC

Effect of T on G_{\parallel} in mixed mode $\beta = 45^{\circ}$ for variours MC



<u>Objectives:</u> analysis the influence of model parameters (Young modulus, load, deflection) on the output parameters (deflection, restitution energy, limit state function)

Evolution of G_{II} versus moisture content for $\beta = 45^{\circ}$

Essais extérieur en ENV. variables (issu de T1.3)



Objectifs: modélisation de la moitié de la poutre soumise à une charge concentrée



Objectifs: modélisation de la réponse structure par le Réseau Bayésien (BN)



Analyse de l'importance des paramètre

Case	Decorintion	Value				Sensitivity			
	Description	flex	G1	G2	Pf	flex	G1	G2	Pf
	Prior	-11.77	0.16	0.76	0.03				
Case 1	Increase 15% mod_E1	-10.97	0.15	0.76	0.03	-7%	-2%	0%	-6%
Case 2	Increase 15% mod_E2	-11.78	0.14	0.67	0.00	0%	-10%	-12%	-94%
Case 3	Increase 15% mod_G12	-11.62	0.16	0.72	0.02	-1%	-1%	-4%	-39%
Case 4	Increase 15% F	-13.41	0.20	0.97	0.11	14%	29%	28%	297%
Case 5	Increase 15% Deflection	-	0.17	0.81	0.05	-	10%	7%	85%
Case 6	Decrease 15% F	-10.74	0.13	0.61	0.00	-9%	-18%	-19%	-100%
Case 7	Decrease 15% Deflection	-	0.15	0.72	0.01	-	-7%	-4%	-82%

Conclusion - Perspectives

- 1. Improve the analytical formulation of T and A integrals Thermo-hydro-mechanical variation effects Generalization to orthotropic materials
- 2. Viscoelasticity and crack growth process

Analytical formulations Incremental formulation

3. Implementation in FE software

Viscoelastic routine Energy release rate with THVM behaviour

3. Coupled mechanic - probabilistic methodology

Mechanical – reliability approaches in Cast3M and Matlab software Importance of mechanical parameters

- A. Moisture variation and mechanosorptive law
- B. Viscoelastic crack growth using mixed mode process zone
- C. Reliability assessment (uncertainties) with TVHM effect
- D. 3D fractures coupling TVHM reliability approaches



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