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

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Climatic conditions

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

External loading

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

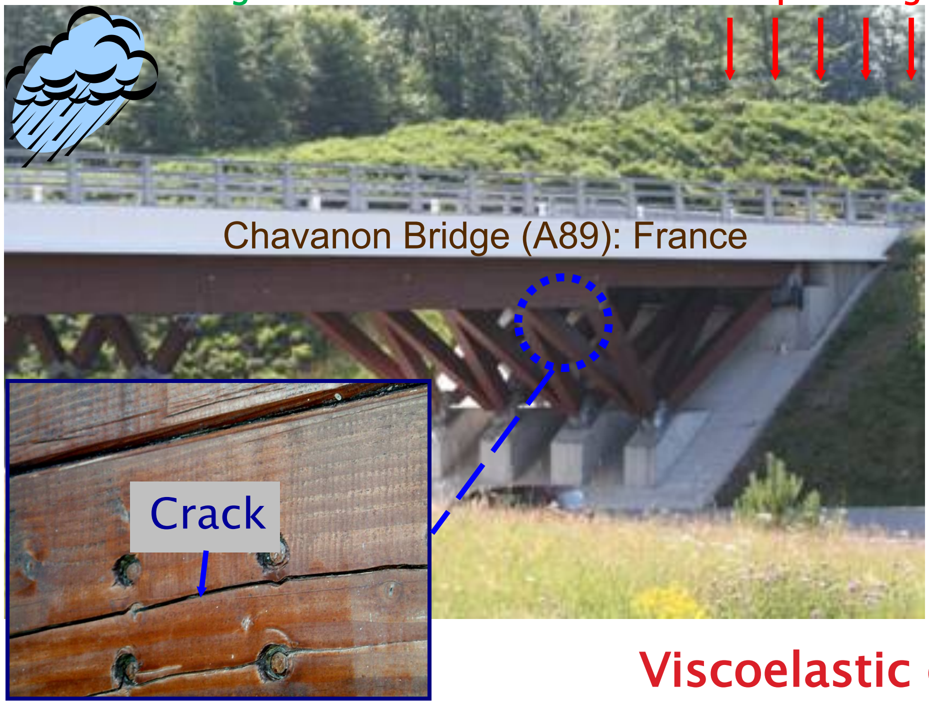
Long term behavior

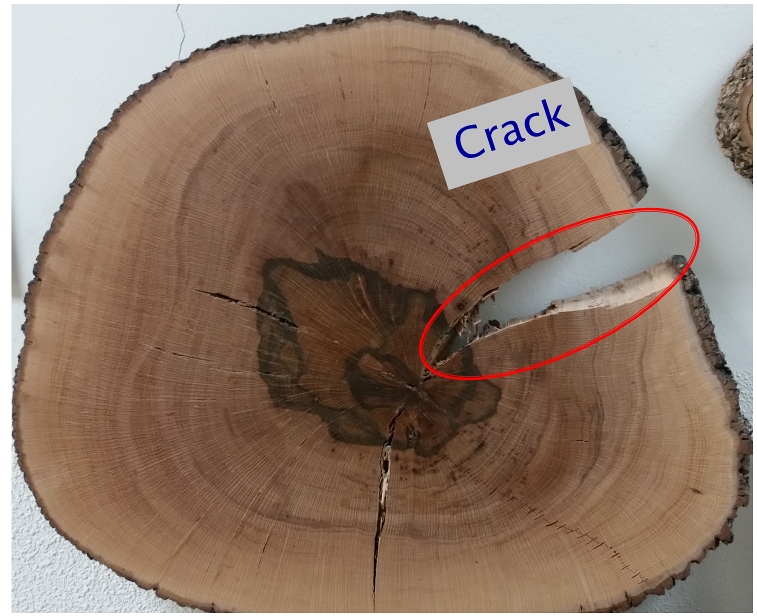
- Acceleration of creep
- Shrinkage-swelling effects
- Development of hydric stresses
- Development of cracks

Scientific context

Complex loadings

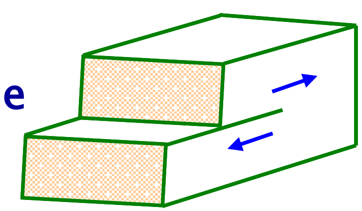
Climatic loadings   Moisture variation   Creep loading

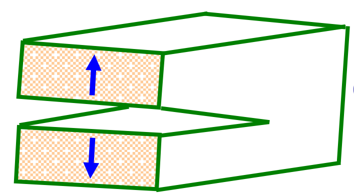




Viscoelastic effects

Shear mode





Opening mode

Mixed-modes crack growth process in time dependent material due to mechanical and environmental loadings

Evaluation of energy release rate in orthotropic materials under environmental effects

In plane configuration

$$A = {}^1G_v + {}^2G_v \rightarrow f({}^1G_v, {}^2G_v, {}^1G_c, {}^2G_c)$$

G in mode I and II

Critical values

Griffith fracture criterion

$$f = \left(\frac{{}^1G_v}{{}^1G_C} + \frac{{}^2G_{vI}}{{}^2G_C} \right) < 1$$

Stationary crack

$$f = \left(\frac{{}^1G_v}{{}^1G_C} + \frac{{}^2G_v}{{}^2G_C} \right) = 1$$

Crack growth

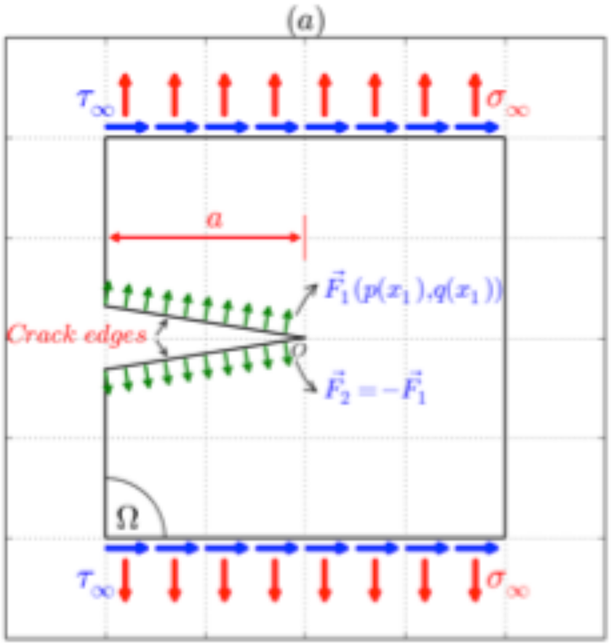
The separation of fracture criteria and viscoelastic characteristics under environmental effects

- 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

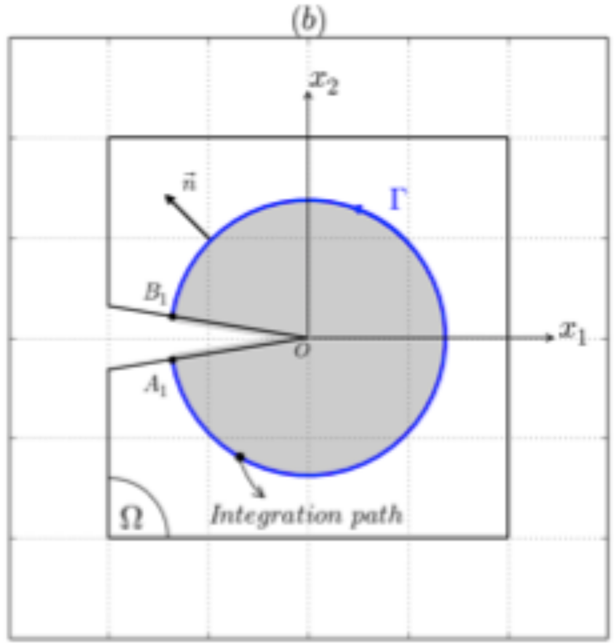
Content

1. **Path independent integrals in orthotropic materials *(T, A)***
2. **Generalization to viscoelastic crack growth materials**
3. **Numerical results and discussions**
4. **Coupled mechanics-reliability methodology**
5. **Conclusions and perspectives**

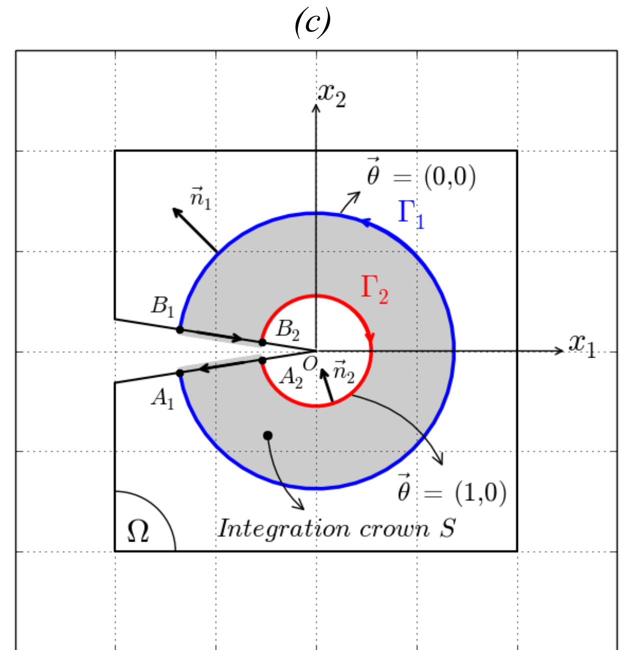
Integration domains



Pressure on crack lips



Curvilinear domain



Surface domain integral

$$\vec{\theta} = (\theta_1 \quad \theta_2)$$

θ : continuously varying from (1,0) to (0,0)

θ = (1,0); θ = (0,0)

Virtual and real displacement fields

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)

$$\varepsilon_{ij}^{v}=\frac{1}{2}(v_{i,j}+v_{j,i})$$
$$\sigma_{ij}^{v}=\lambda\,\delta_{ij}v_{k,k}+\mu(v_{i,j}+v_{j,i})$$
$$T^{v}=0$$

T-integral formulation

$$T=\int_{\Gamma}\frac{1}{2}\left[\sigma_{ij,1}^{v}\,u_i-\sigma_{ij}^{u}\,v_{i,1}-\gamma\Delta T\left(v_{1,j}-\psi_{1,j}\right)+\gamma\Delta T_{,j}(v_1-\psi_1)\right]n_j dl$$

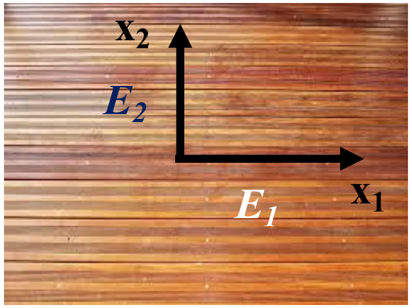
A-integral formulation

$$A=T_\theta=\int_{V}-\underbrace{\frac{1}{2}\left[\sigma_{ij,1}^{v}\,u_i-\sigma_{ij}^{u}\,v_{i,1}\right.}_{A_1:\ \text{Classical term}}-\underbrace{\gamma\Delta T\left(v_{1,j}-\psi_{1,j}\right)+\gamma\Delta T_{,j}(v_1-\psi_1)}_{A_2:\ \text{temperature variation effect}}\left.\right]\theta_{1,j}dV$$

A_1: Classical term

A_2 : temperature variation effect

T and A integrals formulations in orthotropic materials



Plan stress condition

Temperature variation

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ 2\varepsilon_{12} \end{bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{12}/E_1 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & 0 \\ 0 & 0 & 1/G_{12} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} + \begin{bmatrix} \alpha_1 \Delta T \\ \alpha_2 \Delta T \\ 0 \end{bmatrix}$$

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 υ_{12}	0.4
Poisson's coefficient υ_{23}	0.4
Poisson's coefficient υ_{13}	0.4

A integral in static case

Hyp1 : $\gamma = f(E_1, \nu_{12}, \alpha_1)$

$$A = T_\theta = \int_V -\frac{1}{2}\left[\sigma^{v}_{ij,1}\, u_i - \sigma^{u}_{ij}\, v_{i,1} - \gamma \Delta T\left(v_{1,j} - \psi_{1,j}\right) + \gamma \Delta T_{,j}\left(v_1 - \psi_1\right)\right]\theta_{1,j}\, dV$$

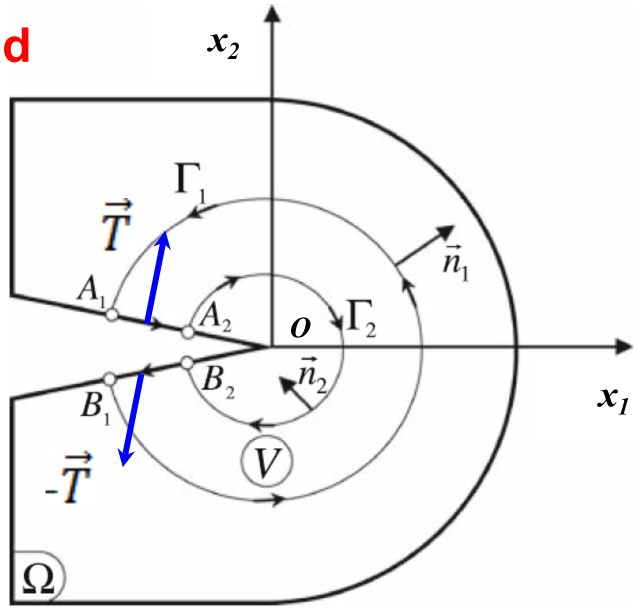
A_1: Classical term

A_2 : temperature variation effect

Numerical domain and load

Applied forces on the crack lips

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



A-integral formulation in crack growth process

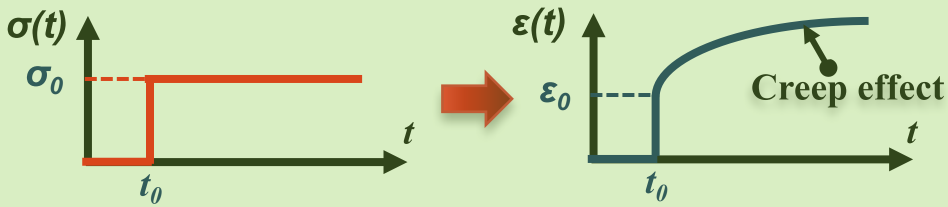
$$A = T_\theta = \int_V \underbrace{-\frac{1}{2}\left[\sigma^v_{ij,1}\, u_i - \sigma^u_{ij}\, v_{i,1}\right.}_{A_1} \underbrace{- \gamma \Delta T\left(v_{1,j} - \psi_{1,j}\right) + \gamma \Delta T_{,j}\left(v_1 - \psi_1\right)}_{A_2}\left.\right]\theta_{1,j} dV$$

A_1: Classical term — **A_2 : temperature variation effect**

$$- \underbrace{\int_{A_1A_2+B_2B_1} T_i\, v_{i,j}\, \theta_j\, dx_1}_{A_3} - \int_V \underbrace{\left[\sigma^v_{ij,k} u_{i,j} + \sigma^u_{ij,k} v_{i,j} + \beta \delta_{ij} u_{i,jk} \Delta T\right]}_{A_4} \theta_k\, dV$$

A_3 : pressure applied on the crack lips — **A_4 : effect of crack growth**

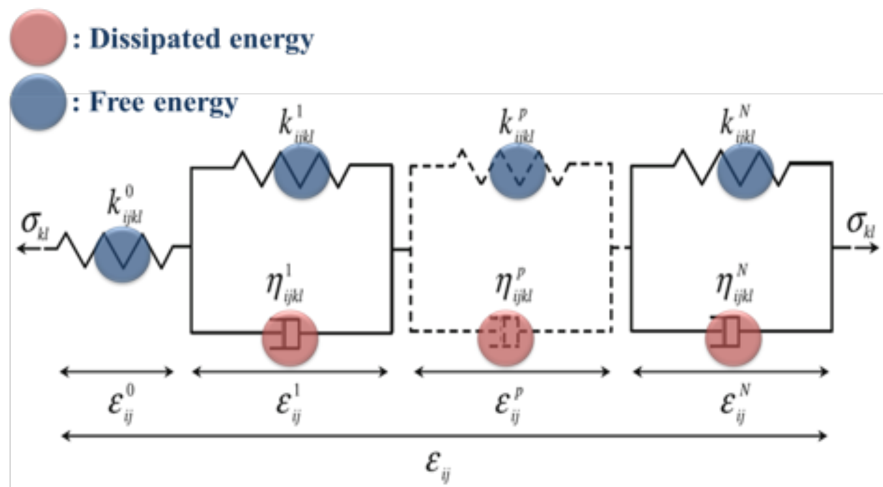
Creep function and BOLTZMANN integral's



$$\varepsilon(t) = J(t_0, t)\sigma(t_0) + \int_{t_0}^{t} J(\tau, t)\, \dot{\sigma}(\tau)\; d\tau$$

Creep tensor

Generalized Kelvin Voigt model



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

$$A^m = \int_\Omega \frac{1}{2}\left[{}^{(m)}\sigma^v_{ij,k}\, u_i^{(m)} - {}^{(m)}\sigma^u_{ij}\, v^{(m)}_{i,k}\right]\theta_{k,j} dS - \int_\Omega \frac{1}{2}\left[\gamma \vartheta_i \delta_{ij} u^{(m)}_{i,jk} \Delta T_{,j}\right]\theta_{k,j} dS$$

$$-\frac{1}{2}\int_\Omega \left[{}^{(m)}\sigma^v_{ij,k}\, u^{(m)}_{i,j} + {}^{(m)}\sigma^u_{ij,k}\, v^{(m)}_{i,j} + \beta\, \delta_{ij}\, u^{(m)}_{i,jk}\, \Delta T\right]\theta_k\, dS$$

Hyp2 : $\beta = g(E_1, \nu_{12}, \alpha_1)$

Real stress intensity factor

Mode I $${}^{u}K_I^{(m)} = \frac{A\theta^{(m)}\left({}^{v}K_I^{(m)} = 1;\ {}^{v}K_{II}^{(m)} = 2\right)}{C_1^{(m)}}$$

Mode II $${}^{u}K_{II}^{(m)} = \frac{A\theta^{(m)}\left({}^{v}K_I^{(m)} = 0;\ {}^{v}K_{II}^{(m)} = 1\right)}{C_2^{(m)}}$$

$C_1^{(m)}$, $C_2^{(m)}$: Viscoelastic compliances

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

$${}^{1}G_v = \sum_p {}^{1}G\theta_v^{(p)} \text{ and } {}^{2}G_v = \sum_p {}^{2}G\theta_v^{(p)} \quad p = m \in \{0,1,\ldots N\}$$

Incremental strain tensor

Strain history

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

Balance equation

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

Apparent Tangent matrix

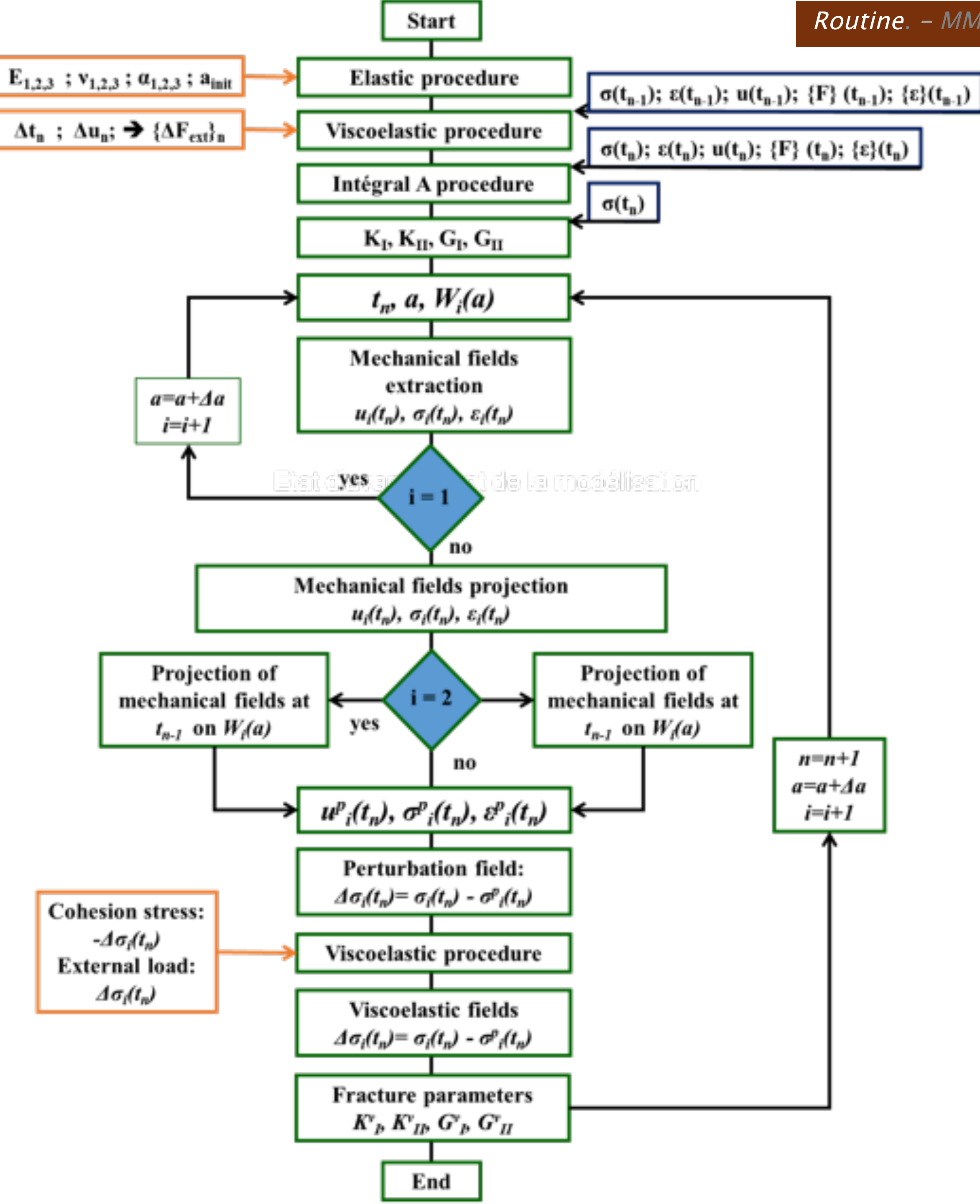
Supplementary viscous load vector

Creep function

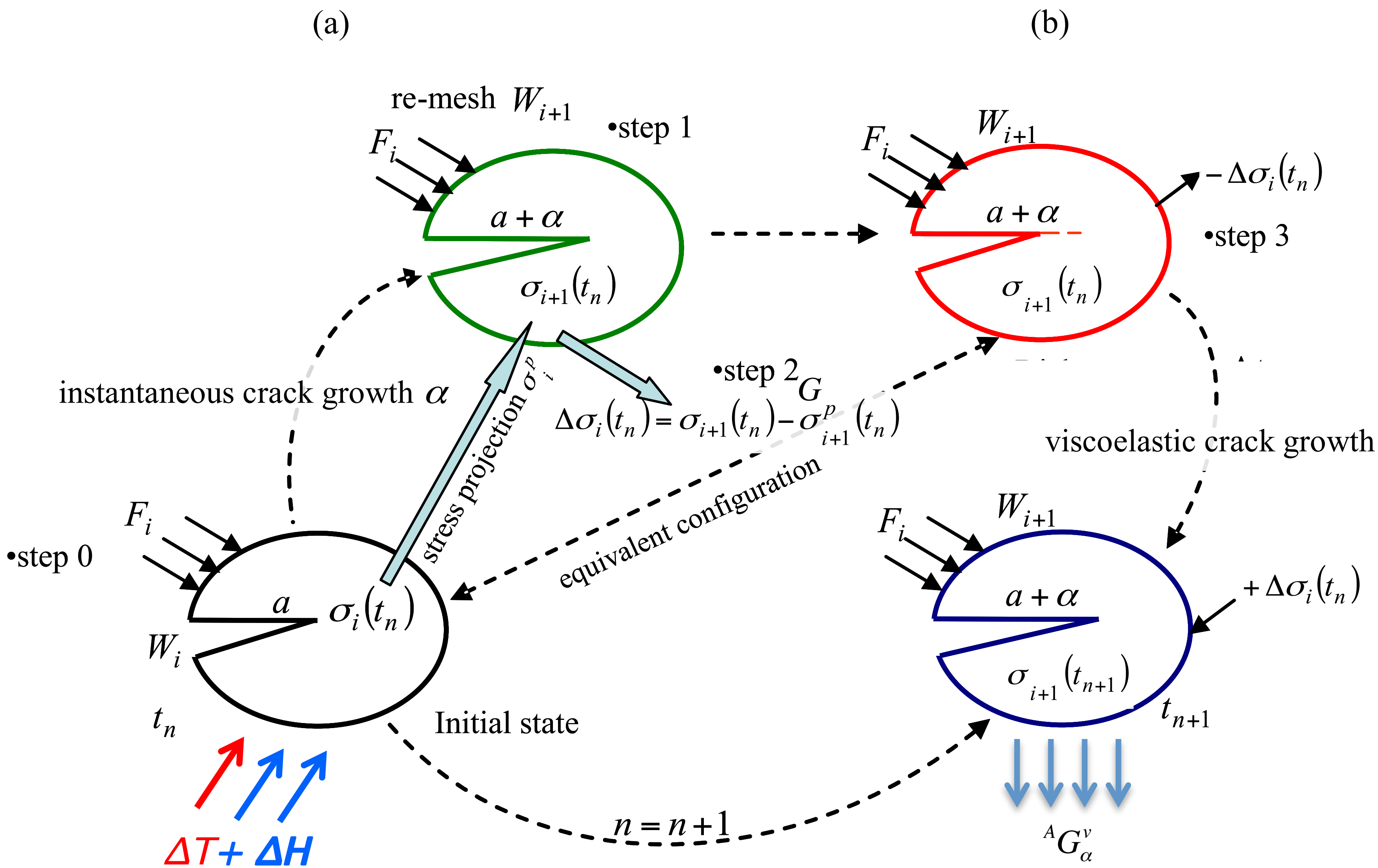
$$J(t) = \frac{1}{E(t)} \cdot C_0 \quad \text{with} \quad C_0 = \begin{bmatrix} 1 & -\upsilon & 0 \\ -\upsilon & E_X / E_Y & 0 \\ 0 & 0 & E_X / G_{XY} \end{bmatrix}$$

$$\frac{1}{E(t)} = \frac{1}{E_X}\left[1 + \frac{1}{74.3}\left(1 - e^{-\frac{74.3}{3.37}t}\right) + \frac{1}{74.4}\left(1 - e^{-\frac{74.4}{33.37}t}\right)\right]$$

Crack growth viscoelastic routine

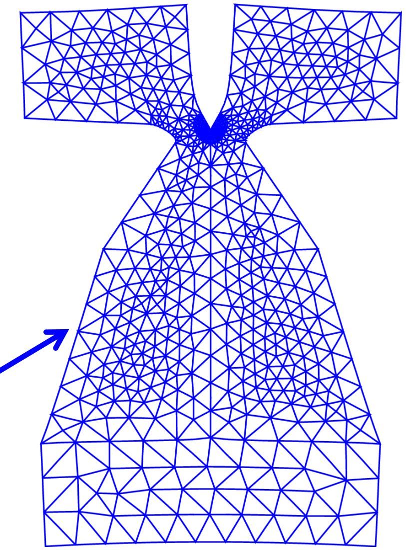


Crack growth viscoelastic simplified routine

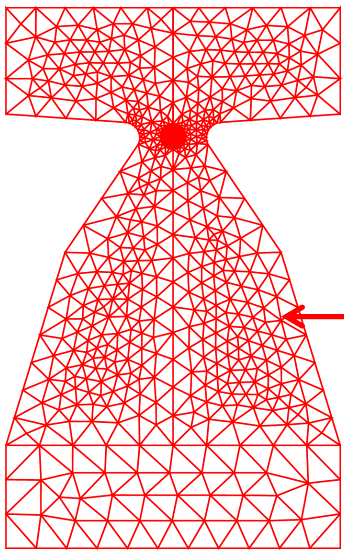


Mixed Mode Crack Growth specimen

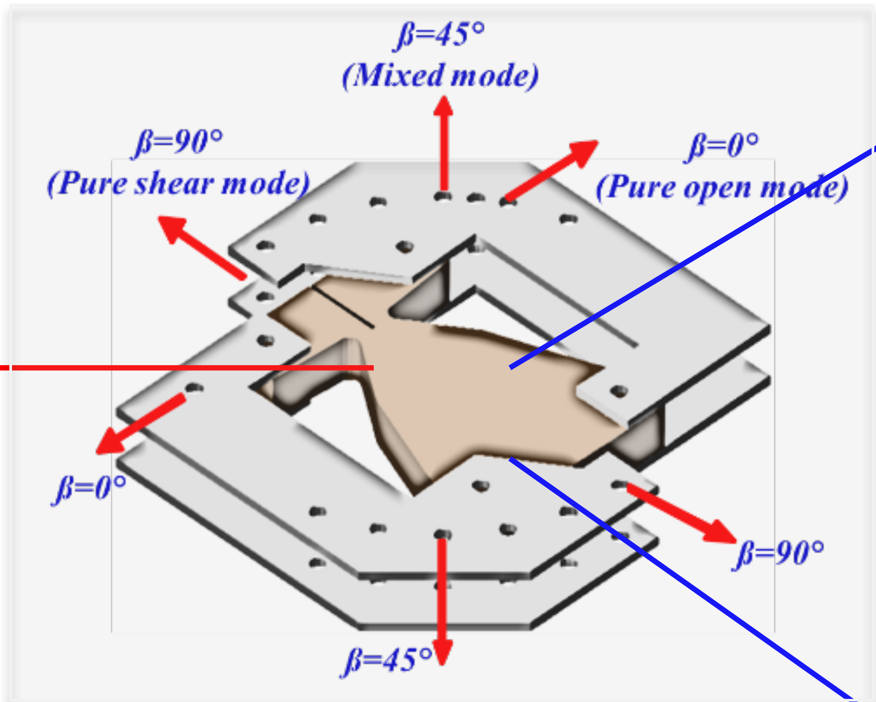
In mode I



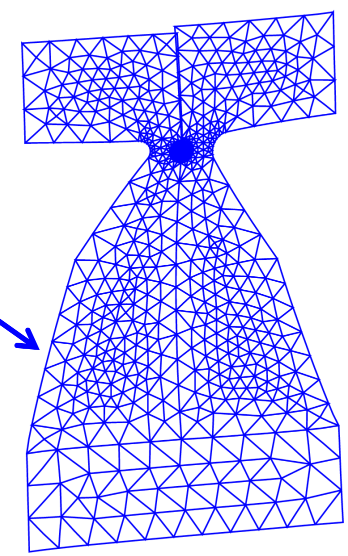
Mesh of wood specimen



MMCG specimen



In mode II

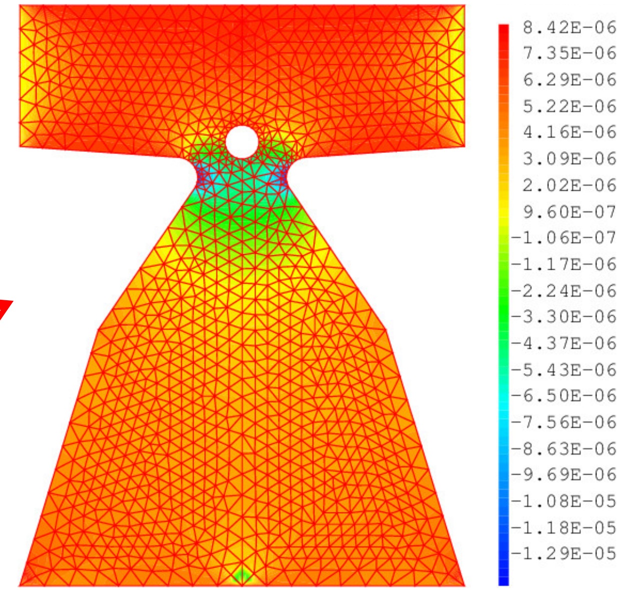


Numerical MMCG mesh with TH variations

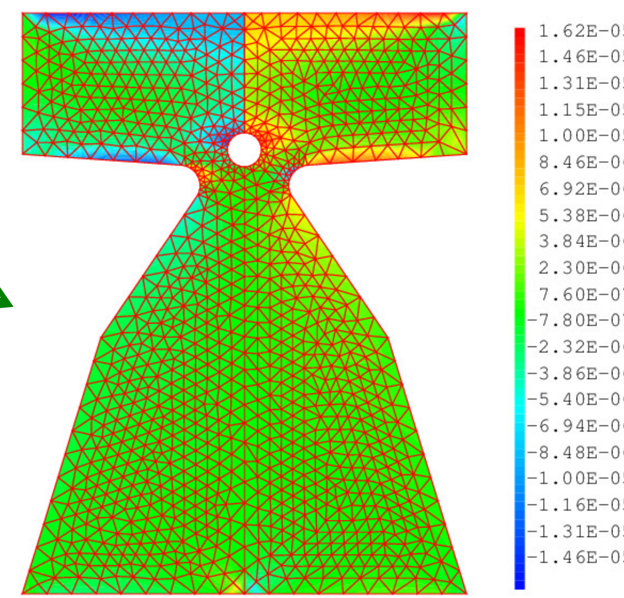
Numerical mesh of wood specimen under Thermo-visco-hydro-Mechanical (TVHM) fields at 12% of internal moisture content

Real wood specimen

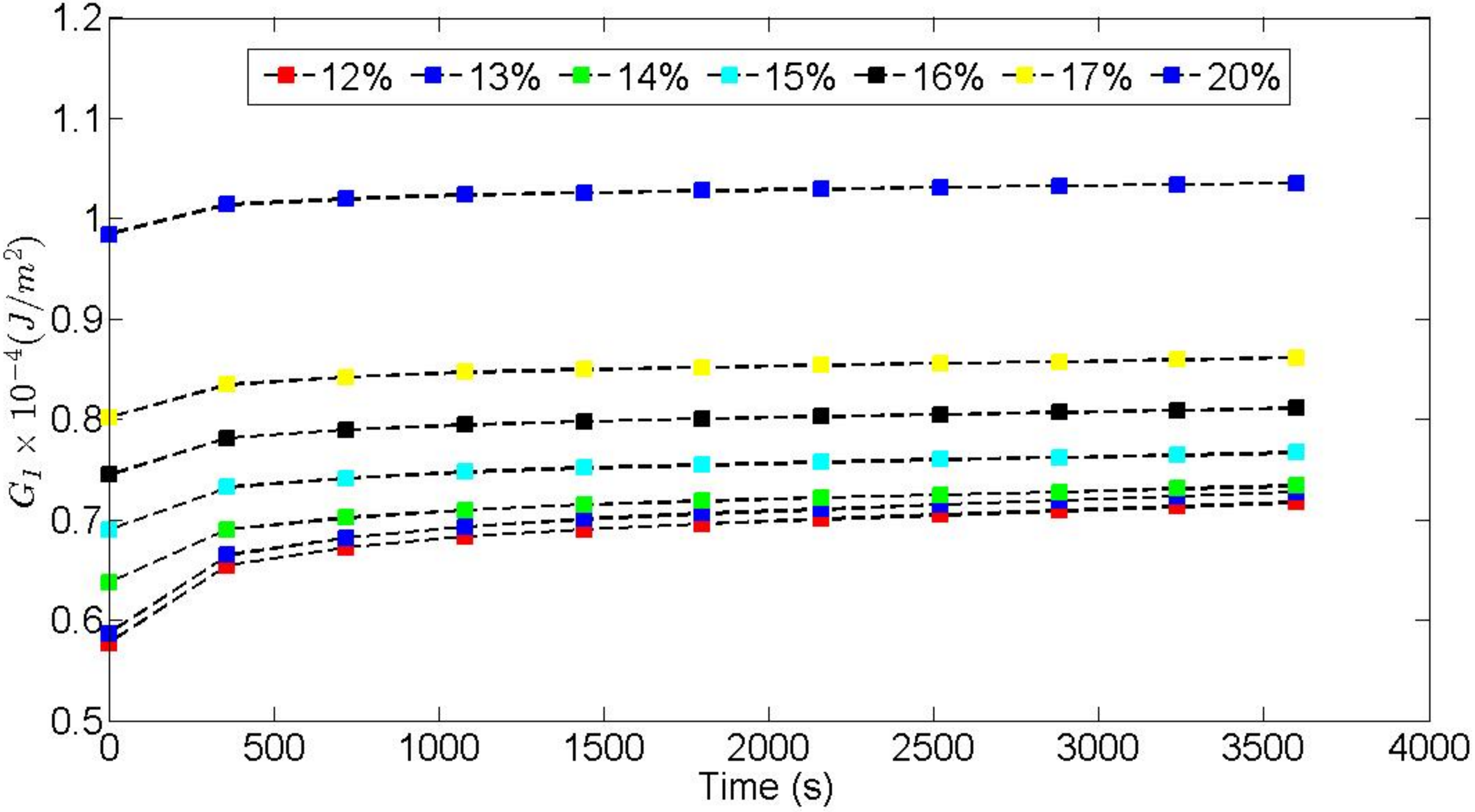
Exx direction



Eyy direction

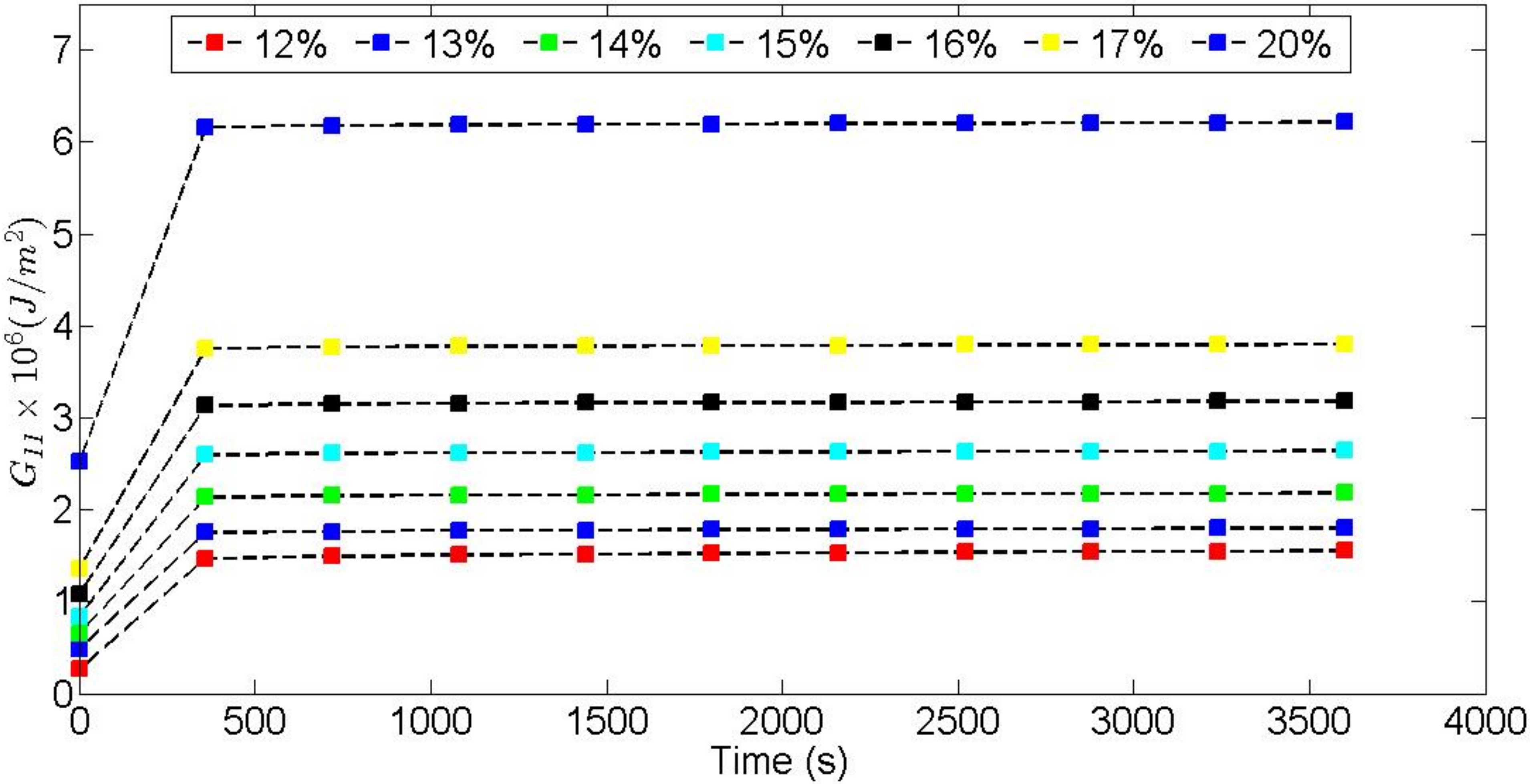


G_I in opening mode versus time under moisture content



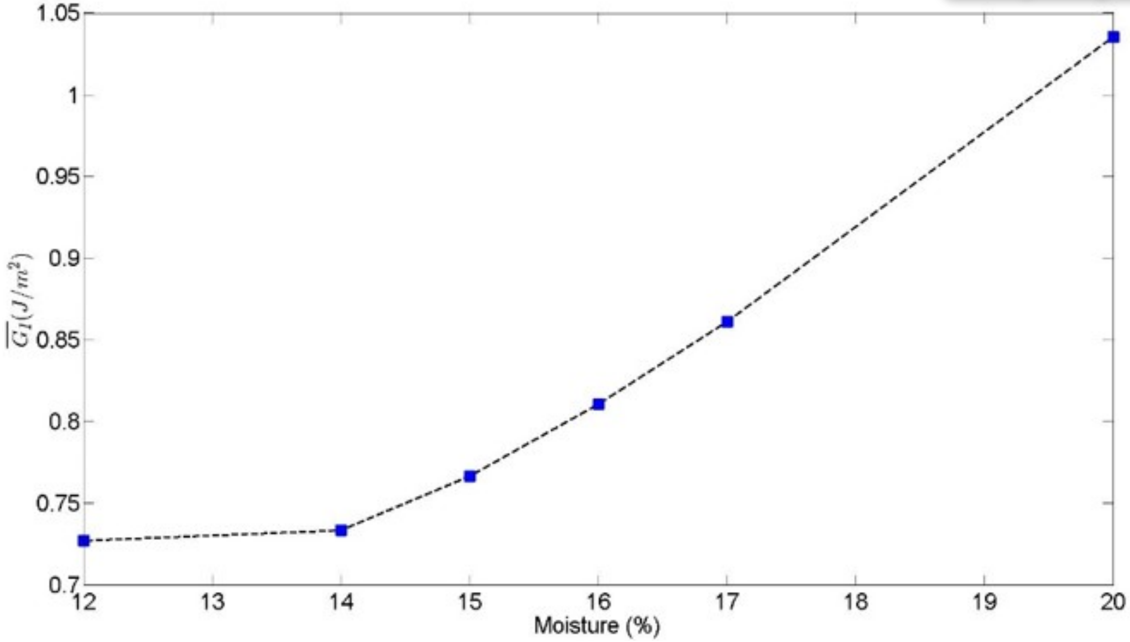
Evolution of G_I versus crack a for *β=45°*

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

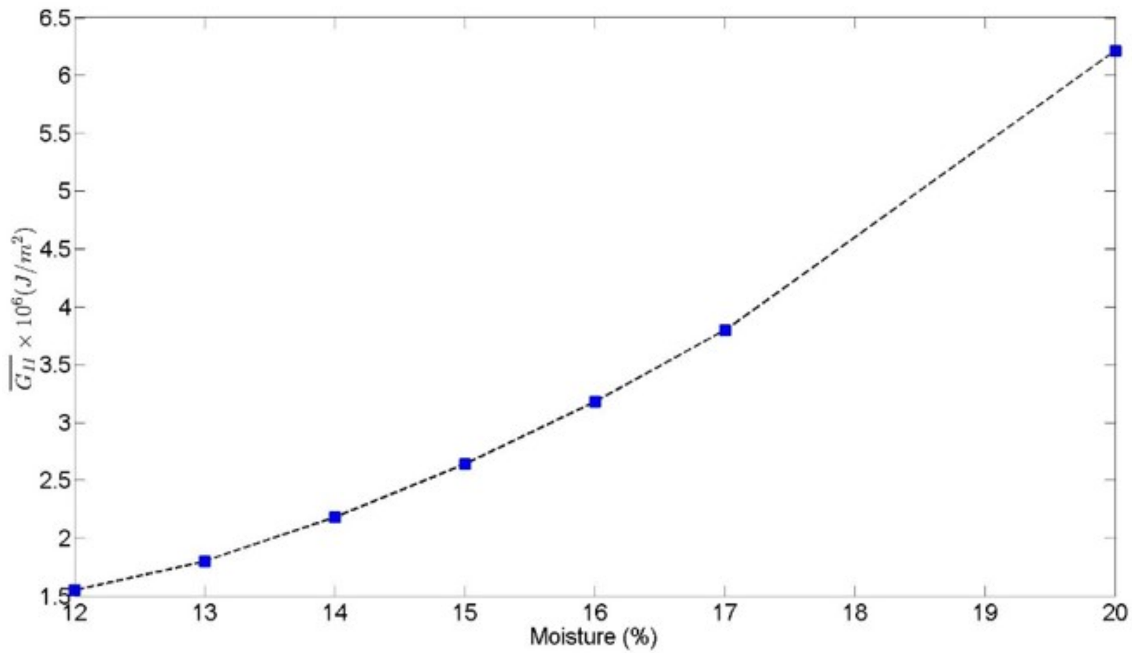


Evolution of G_{II} versus crack a for *β=45˚*

G_I in opening mode versus time under moisture content

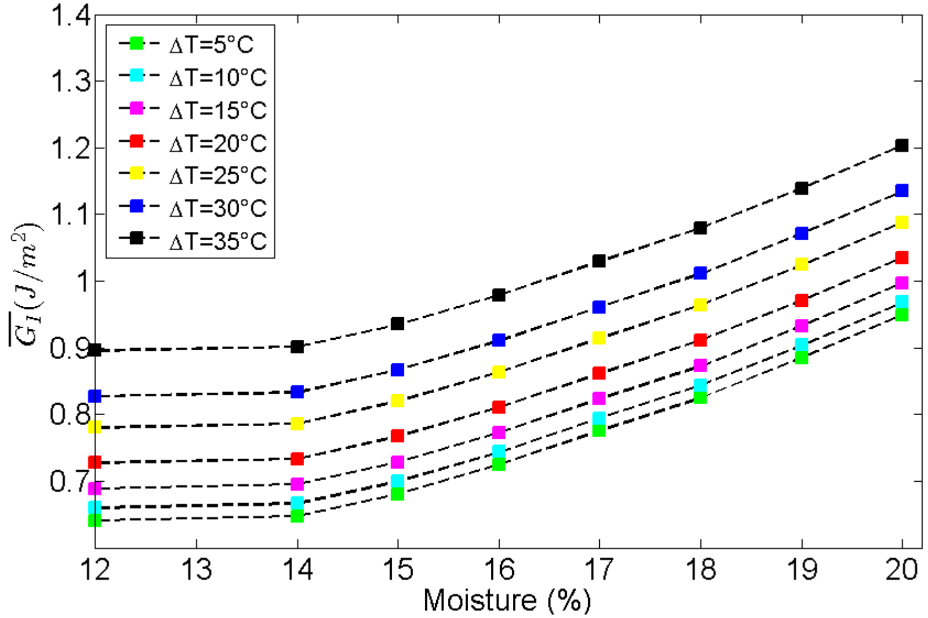


Evolution of G_I versus moisture content for *β = 45°*

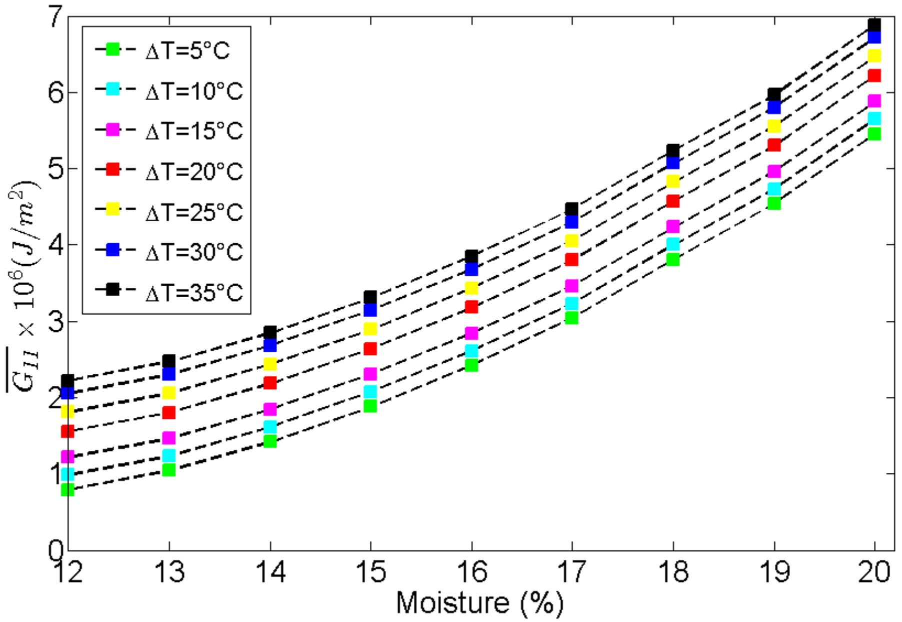


Evolution of G_{II} versus moisture content for *β = 45°*

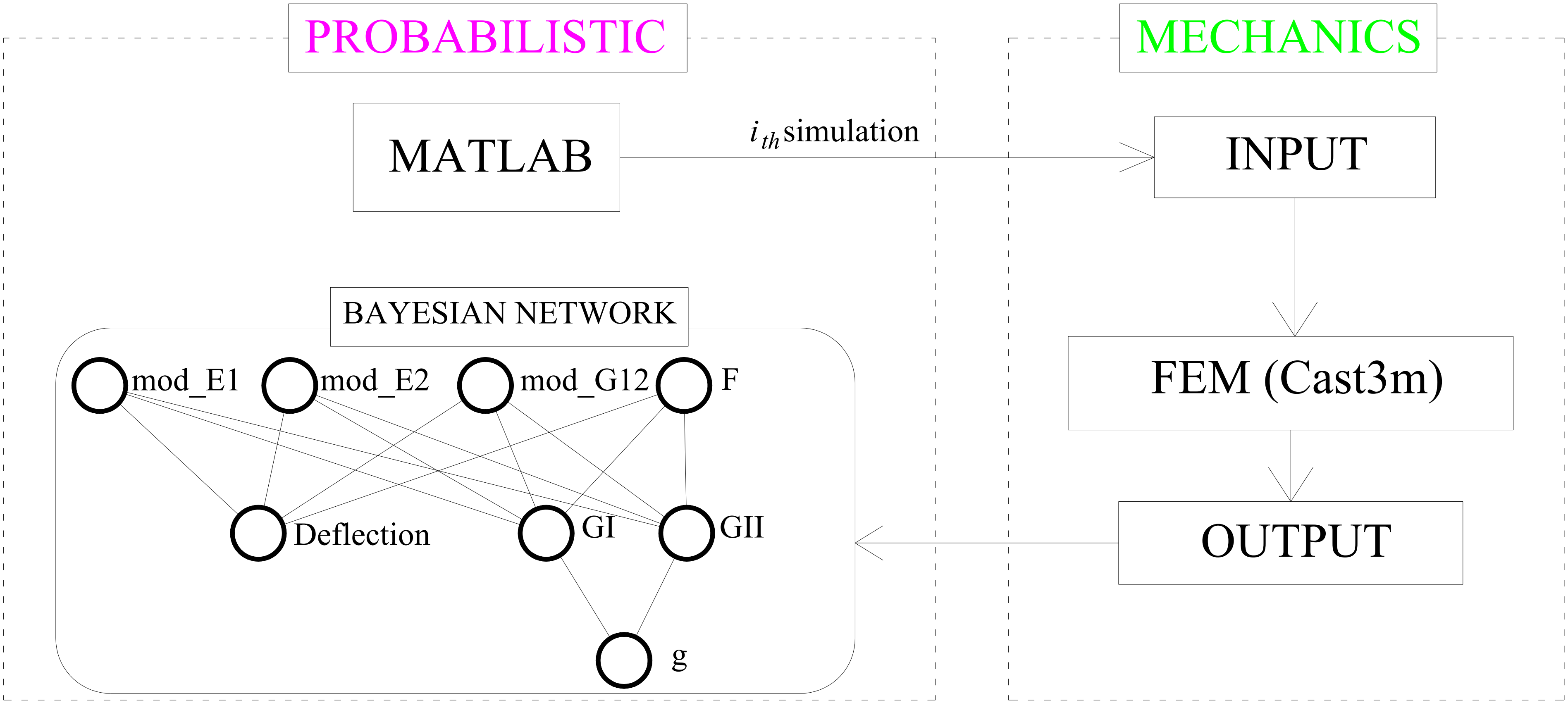
G in mixed mode versus time under moisture content and T°



Effect of T on G_I in mixed mode
***β = 45°* for various MC**



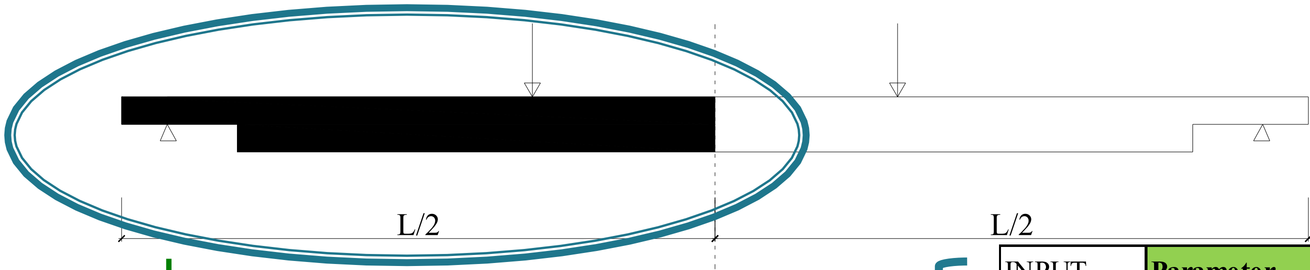
Effect of T on G_{II} in mixed mode
***β = 45°* for various MC**



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

Outdoor tests under varying environnemental conditions

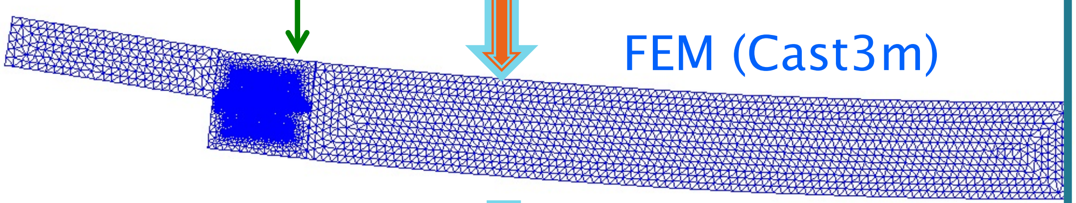
Objectives: modeling of half of the beam subjected to a concentrated load



2000 inputs

Matlab

FEM (Cast3m)



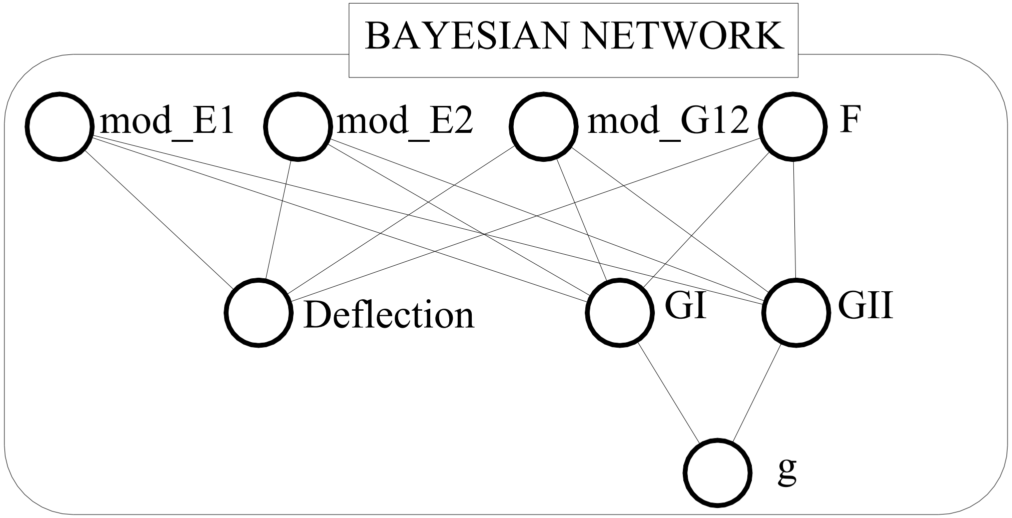
2000 outputs

Probabilistic

(Bayesian Network)

INPUT	Parameter	Value
Geometry	L (mm)	3900
	H (mm)	180
	b (mm)	60
Load	P (N)	Normal(μ=5000; COV=0.1)
Material	mod_E1 (Mpa)	Lognormal (μ=13e3; COV=0.2)
	mod_E2 (Mpa)	Lognormal (μ=650; COV=0.15)
	mod_E3 (Mpa)	1000
	mod_G12 (Mpa)	Lognormal (μ=745; COV=0.15)
	cp_v12	0.42
	cp_v13	0.38
	cp_v23	0.31
	cl_dila1	2e-6
	cl_dila2	5e-5
	d_ortho	(1. 0.)
	G1C (N/m)	300
	G2C (N/m)	1800

Objectives: Modeling of structure response by the Bayesian Network (BN)



Mechanics stage

↓ data

Conditional Probability Table (CPT)

Ex: The CPT of GI is defined :
P(GI|mod_E1, mod_E2, mod_G12, F)

↓

Build BN

↓ 7 analysis cases

Updating

Analysis of the importance of setting

Case	Description	Value				Sensitivity			
		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%

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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