Integration of rapid variation of moisture content in a cohesive zone model: simulation of crack propagation in wood under the humidity variation

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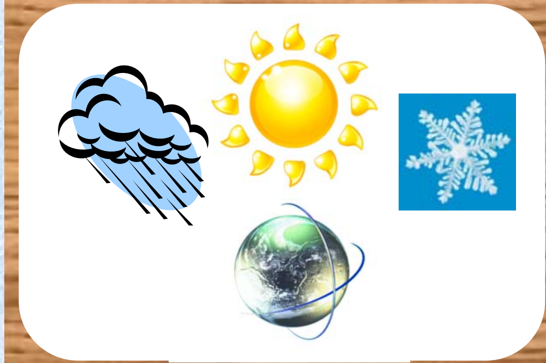
Projet VS2C :

Introduction



Relative Humidity

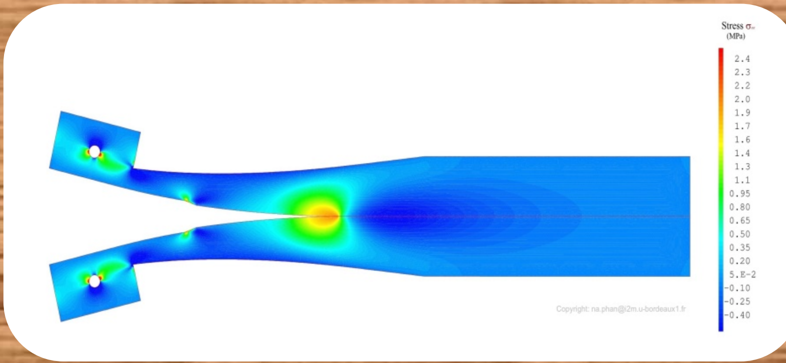
Wood :

* hygroscopic

* quasi-brittle

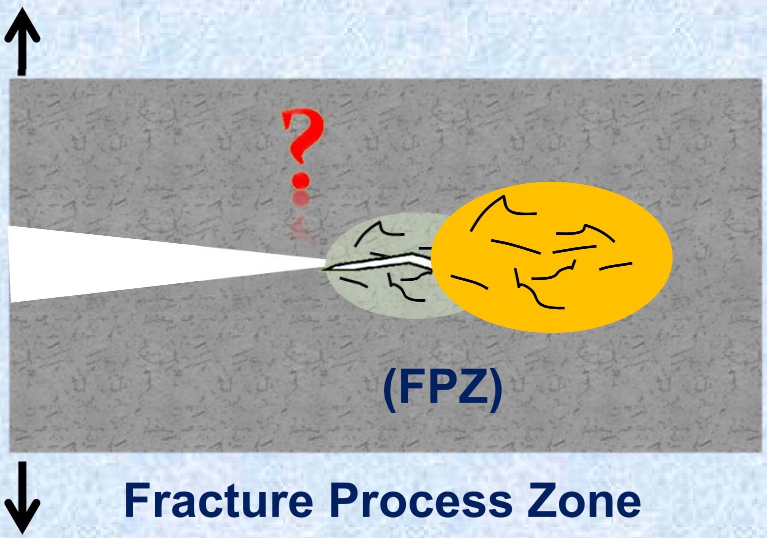
Objective

Influence

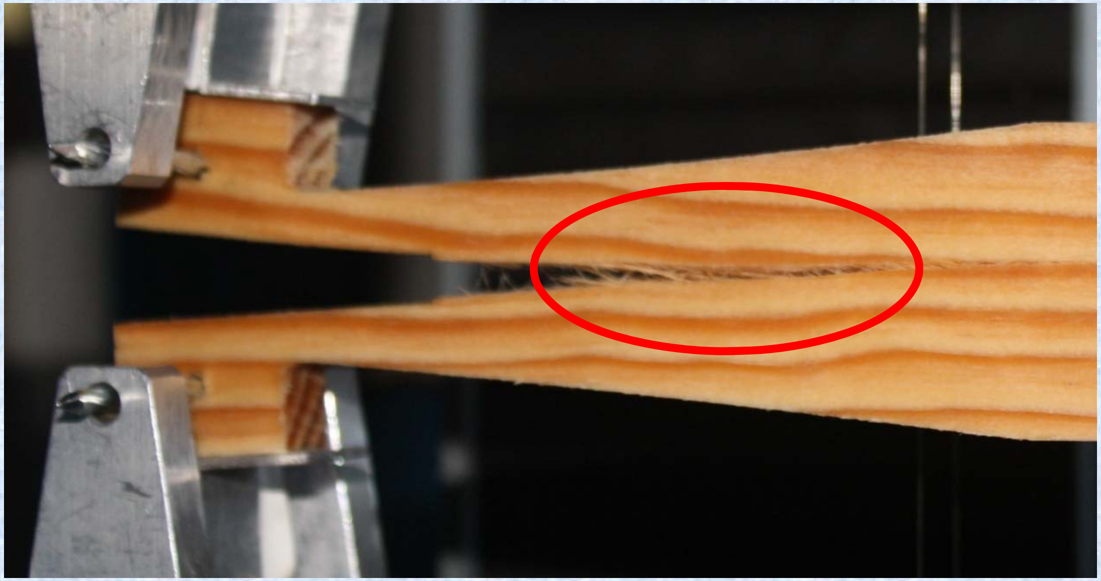


Crack propagation

- Mechanical properties depend on the temperature and the moisture content.
- Varying moisture induces internal stresses → may cause the crack propagation.



Fracture Process Zone

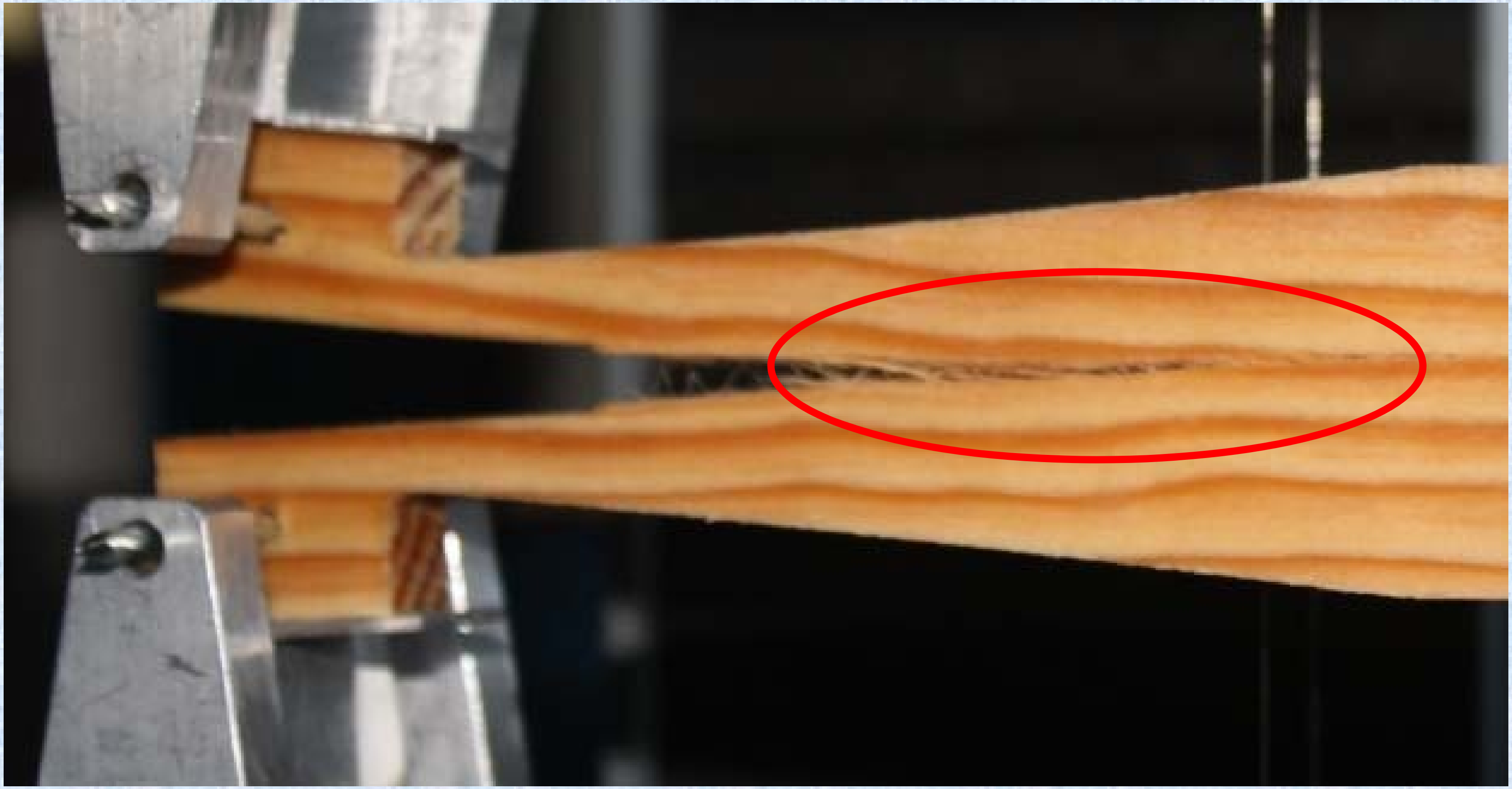


Plan

- Linear Elastic Fracture Mechanics equivalent
- R-curve and Cohesive Zone Model (CZM)
- Integration of rapid variation of *MC* in CZM
- Our model and results
- Conclusions and perspectives

Linear Elastic Fracture Mechanics equivalent

- The ***crack length*** monitoring during its growth ***is very difficult to be accurately performed on wood.***
- Due to the presence of FPZ at the crack tip, LEFM cannot be directly applied to estimate the fracture energy → **'equivalent LEFM'** is usually applied on the quasi-brittle fracture and provides useful approximations (Bazant and Planas (1998); Morel et al (2005)).



Linear Elastic Fracture Mechanics equivalent

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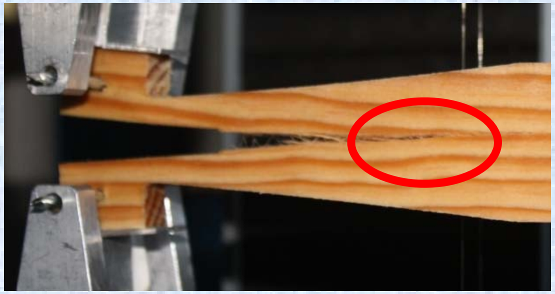
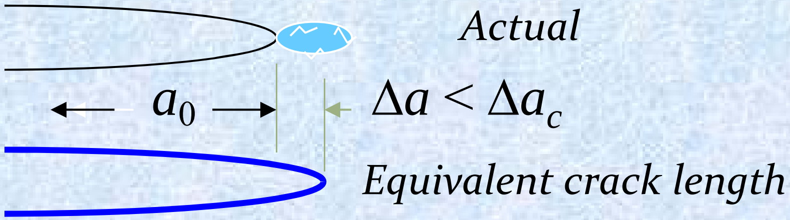
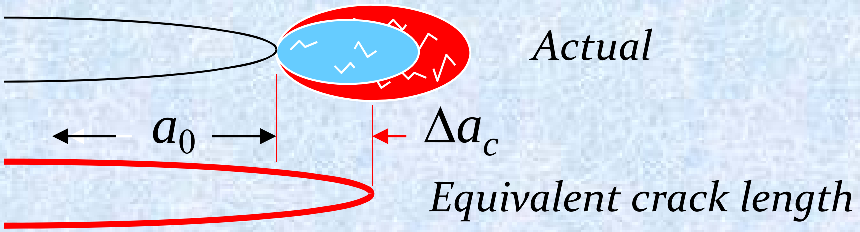


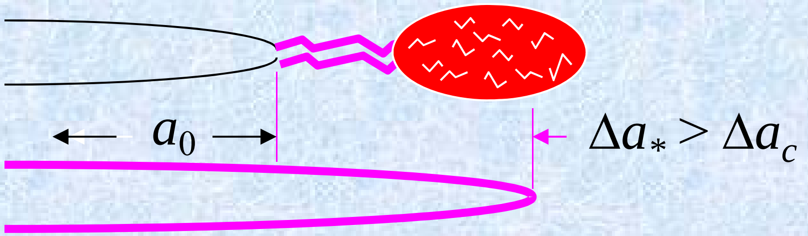
- **Development of FPZ**

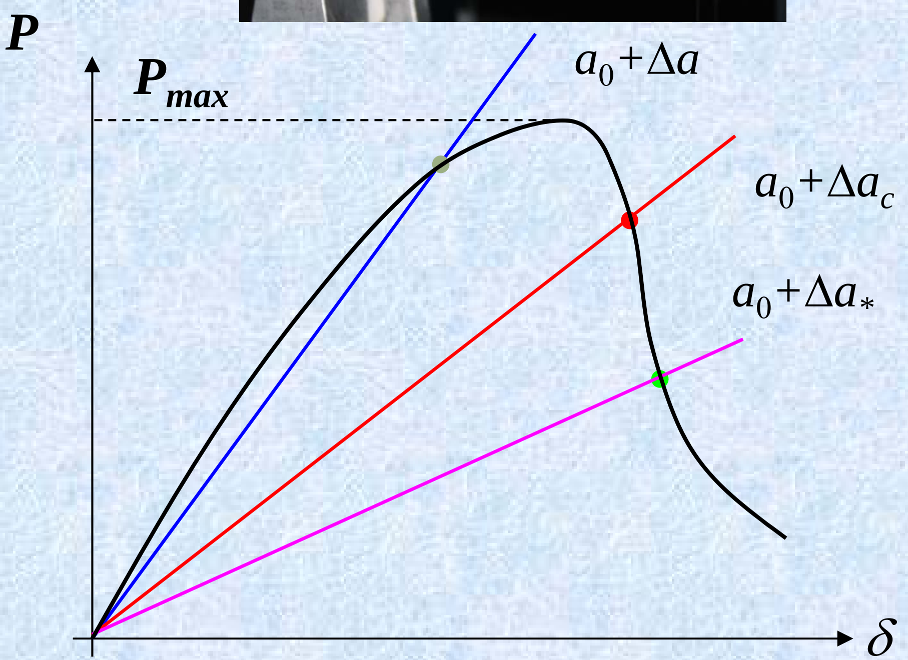


- **Critical size of FPZ**



- **Propagation of FPZ**

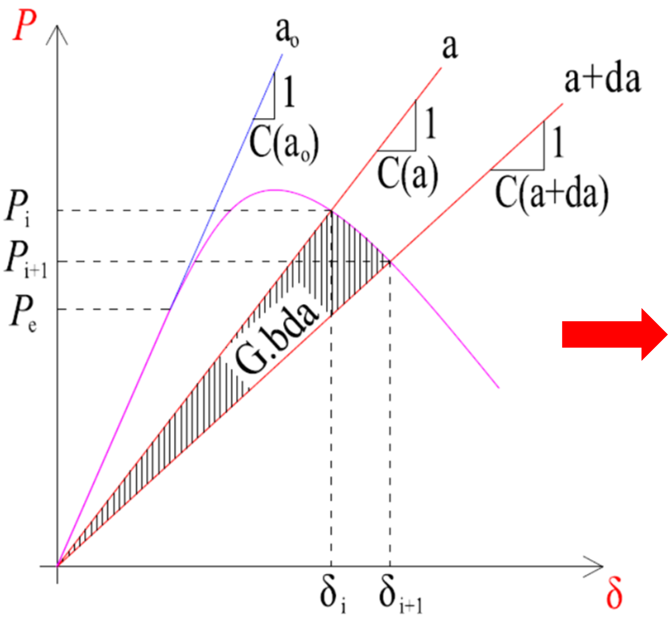


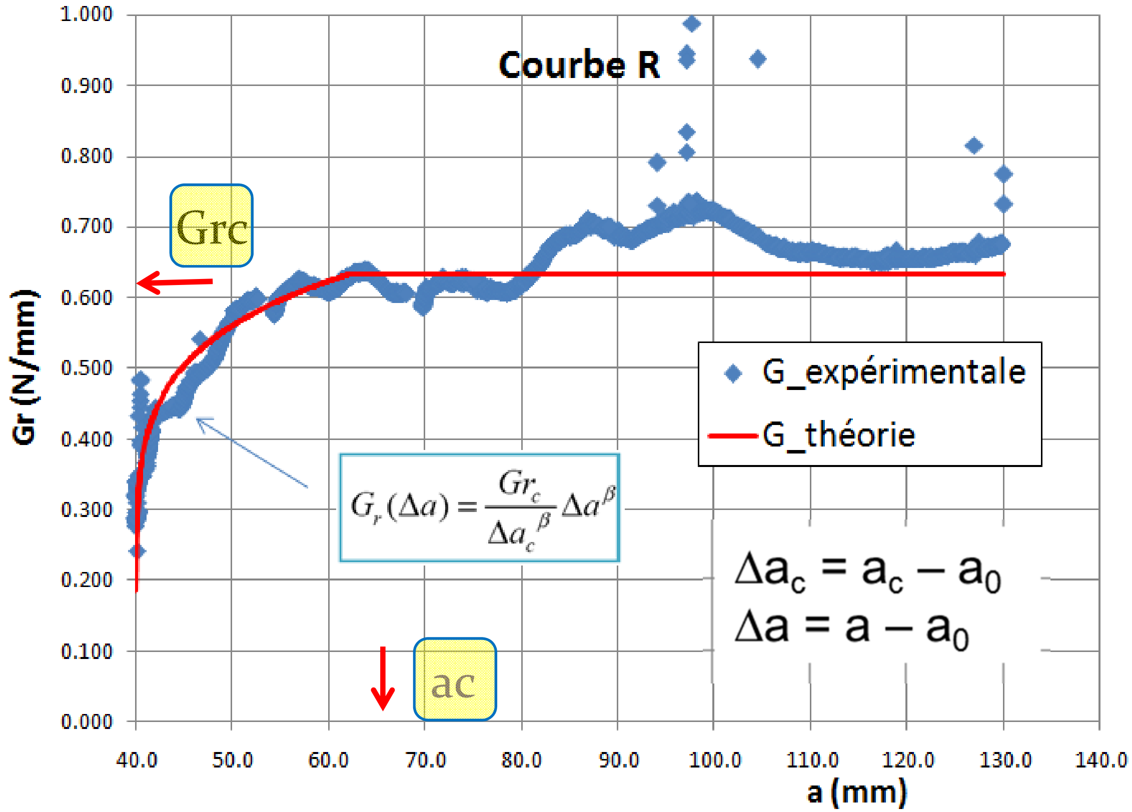


Load – displacement curve

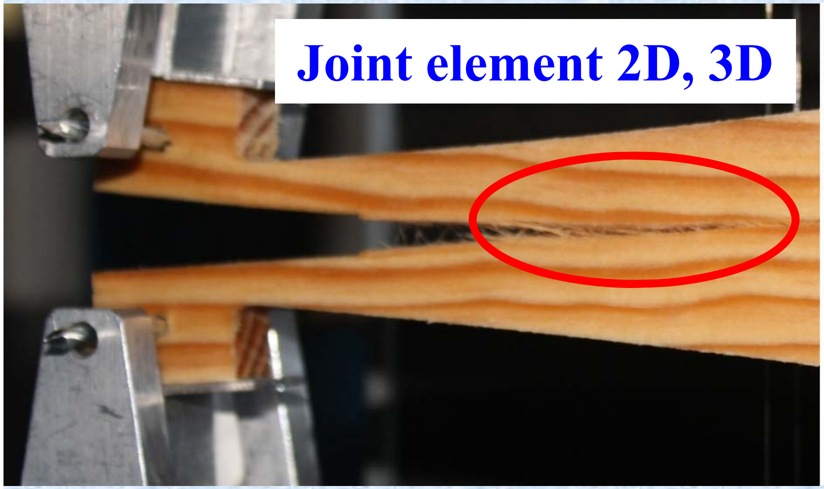
R-curve determination

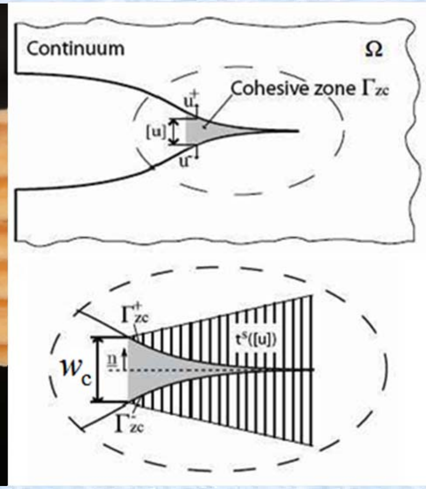
$$G(a) = \frac{P^2}{2b} \cdot \left[\frac{\partial C(a)}{\partial a} \right] = G_R(a)$$





Cohesive Zone Model (CZM)





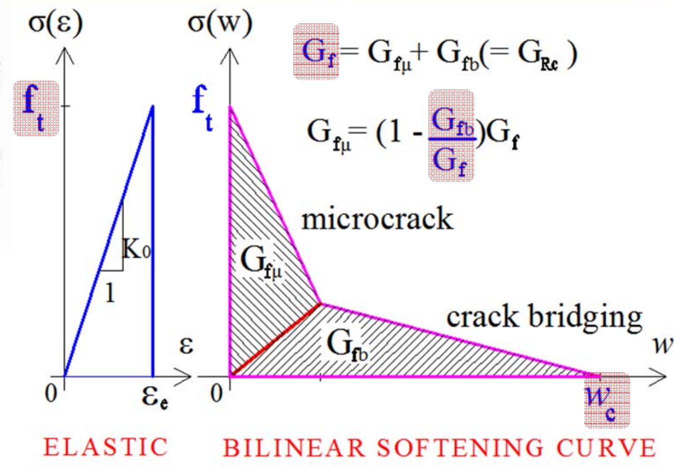
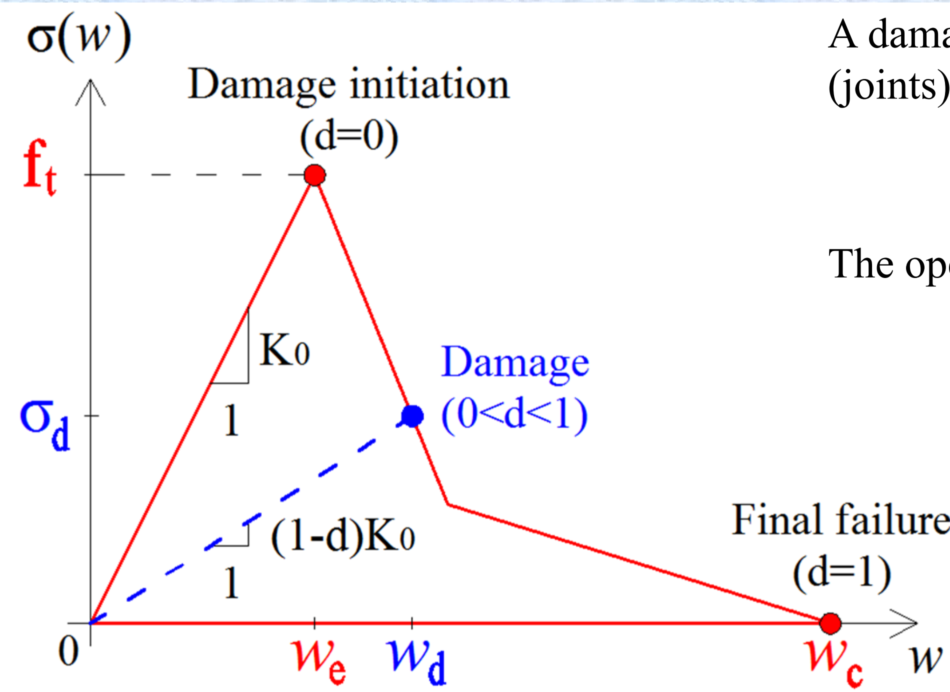


Illustration of the bilinear traction-seperation law (STL) in CZM



A damage parameter d is used to describe the interface state (joints):

$$d = \frac{w_d f_t - w_e \sigma_d}{w_d f_t}$$

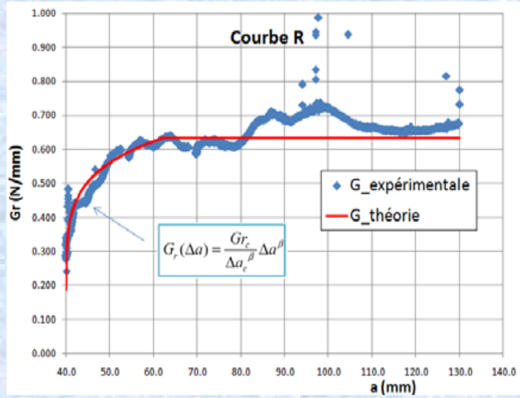
The opening stress is related to the opening displacement w :

$$\begin{cases} \sigma = K_o w & if\ w \le w_e \\ \sigma = (1-d)\, K_o w & if\ w_e < w < w_c \\ \sigma = 0 & if\ w \ge w_c \end{cases}$$

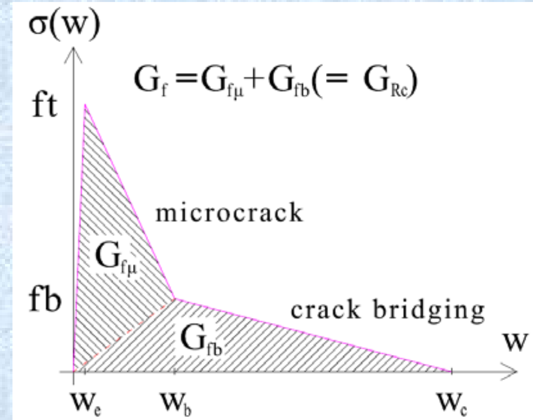
w_d is the maximum separation for the interface element over the entire loading history.

Parameter identification of CZM

R-curve ($G_f = G_{Rc}$)



Parameters of CZM
($f_t, w_c, {G_{f\mu}}/{G_f}$)



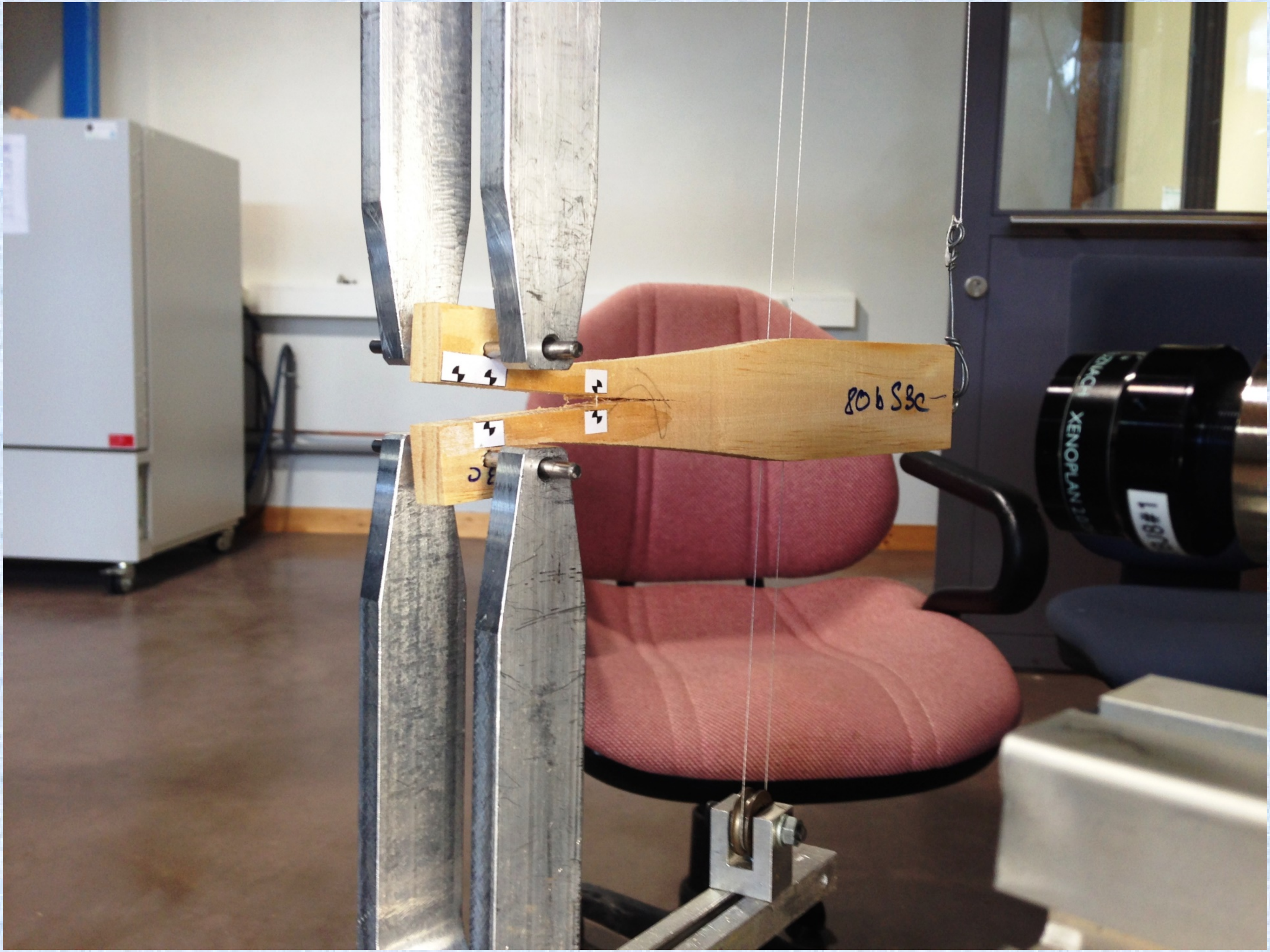
Cast3m

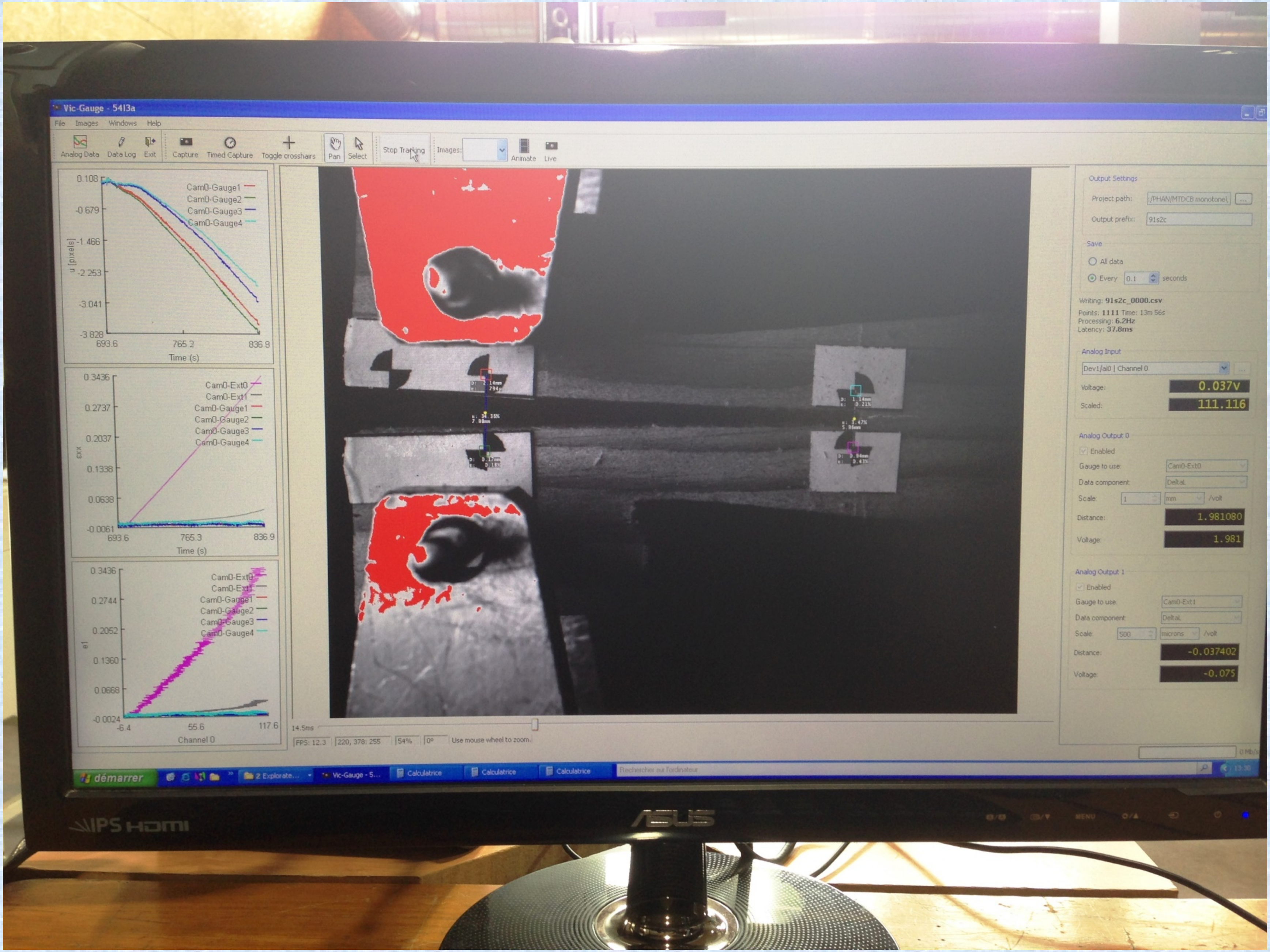
Numerical results

Experimental data

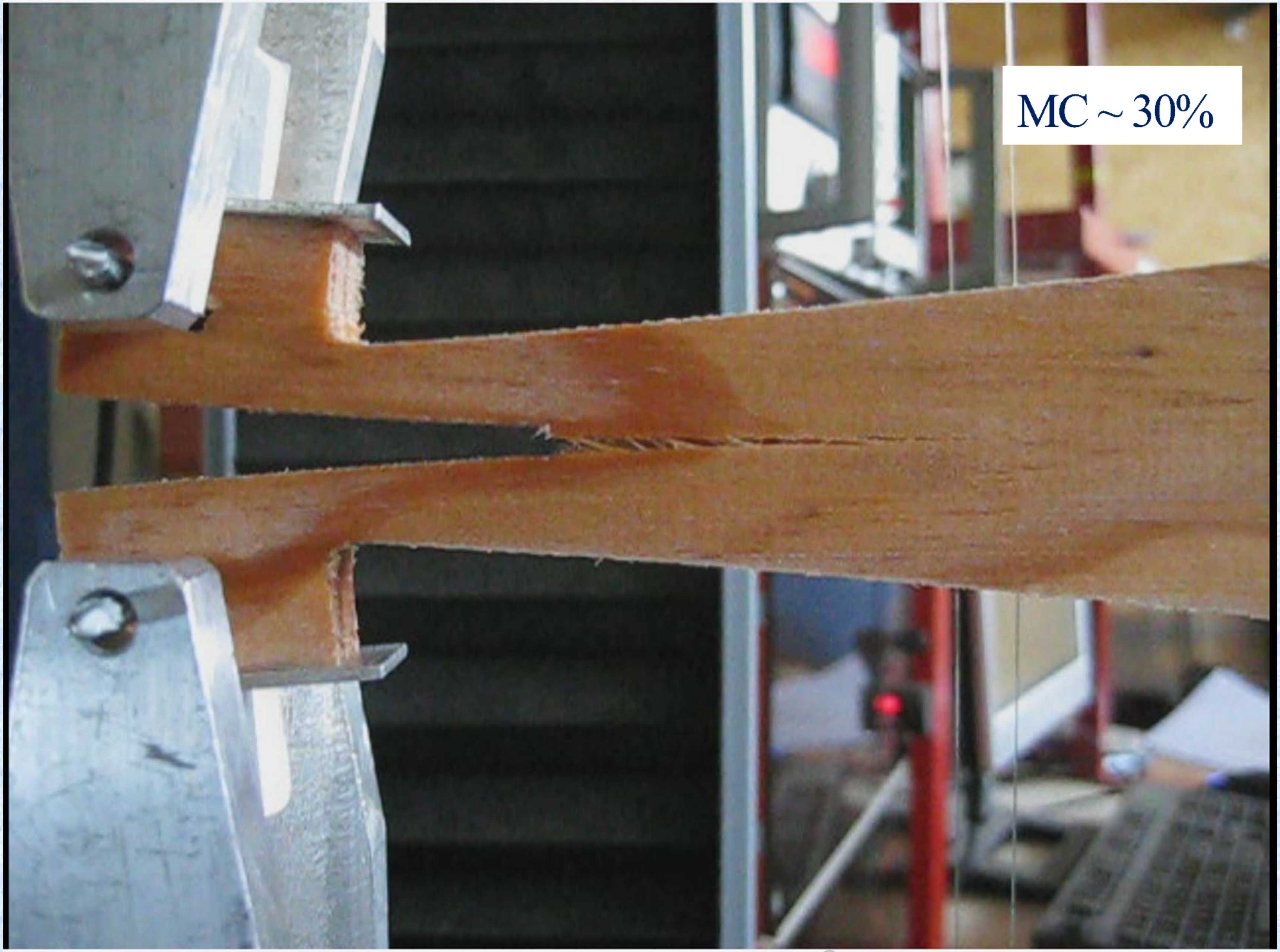
Identification

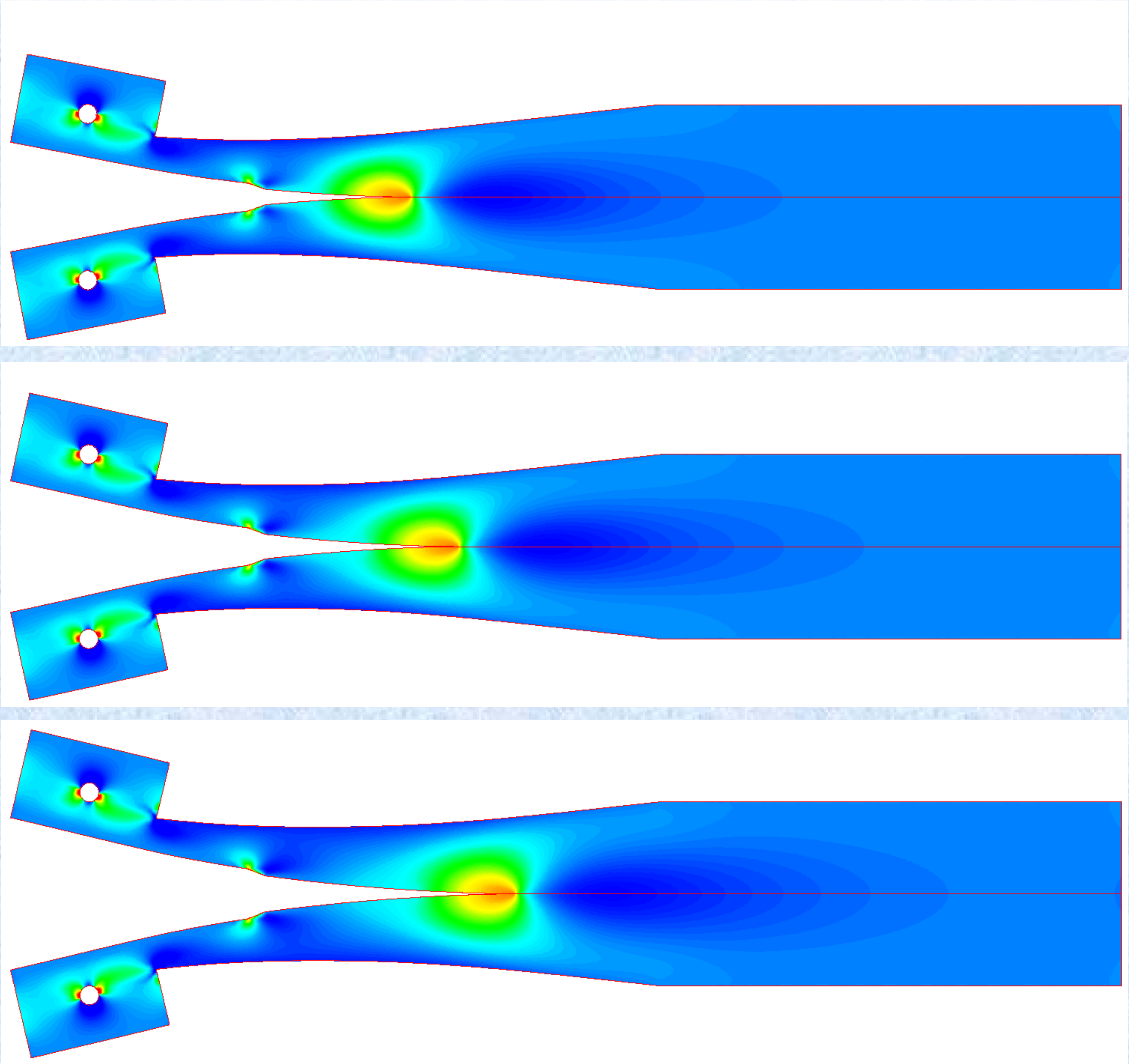
Conclusion

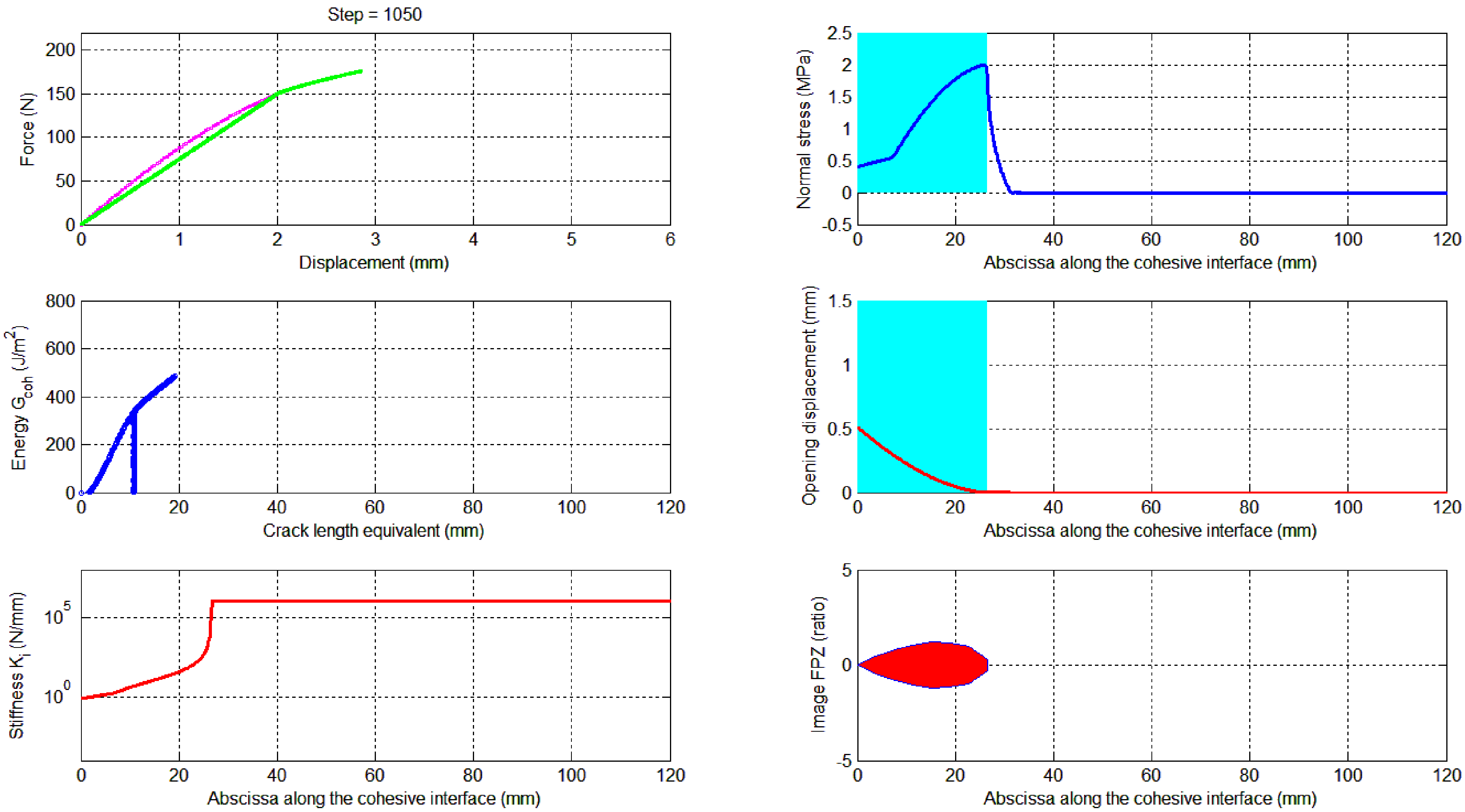

80 b SBc

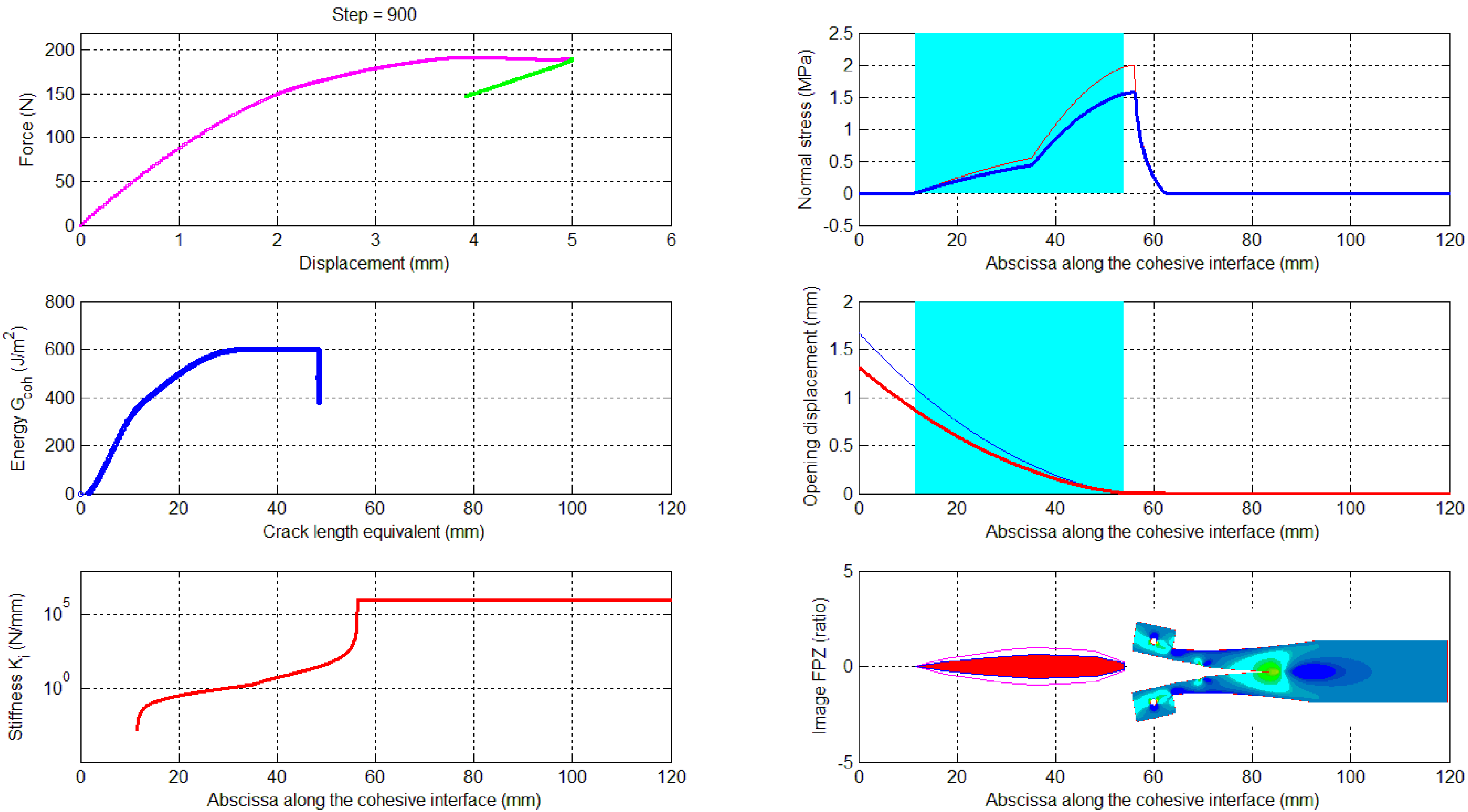

Vic-Gauge - 5413a
File
Images
Windows
Help
Analog Data
Data Log
Exit
Capture
Timed Capture
Toggle crosshairs
Pan
Select
Stop Tracking
Images:
Animate
Live
Cam0-Gauge1
Cam0-Gauge2
Cam0-Gauge3
Cam0-Gauge4
Time (s)
Cam0-Ext0
Cam0-Ext1
Channel 0
Output Settings
Project path:
Output prefix:
Save
All data
Every
seconds
Writing: 91s2c_0000.csv
Analog Input
Voltage:
Scaled:
0.037V
111.116
Analog Output 0
Enabled
Gauge to use
Data component
Scale
Distance:
1.981080
1.981
Analog Output 1
-0.037402
-0.075
Use mouse wheel to zoom.
démarrer
Calculatrice
ASUS
IPS HDMI


MC = 12%
3x36
5115

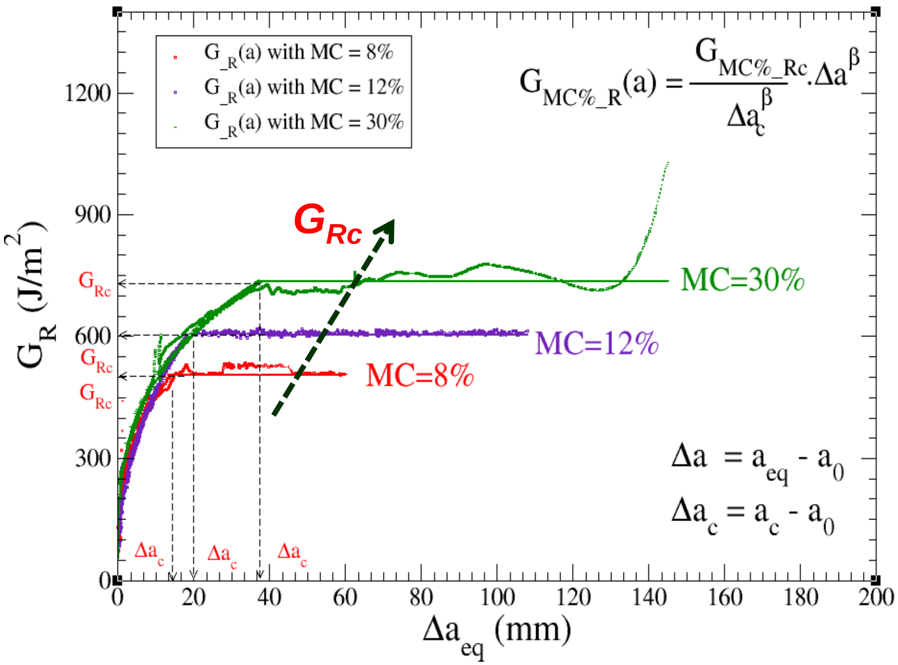

MC ~ 30%

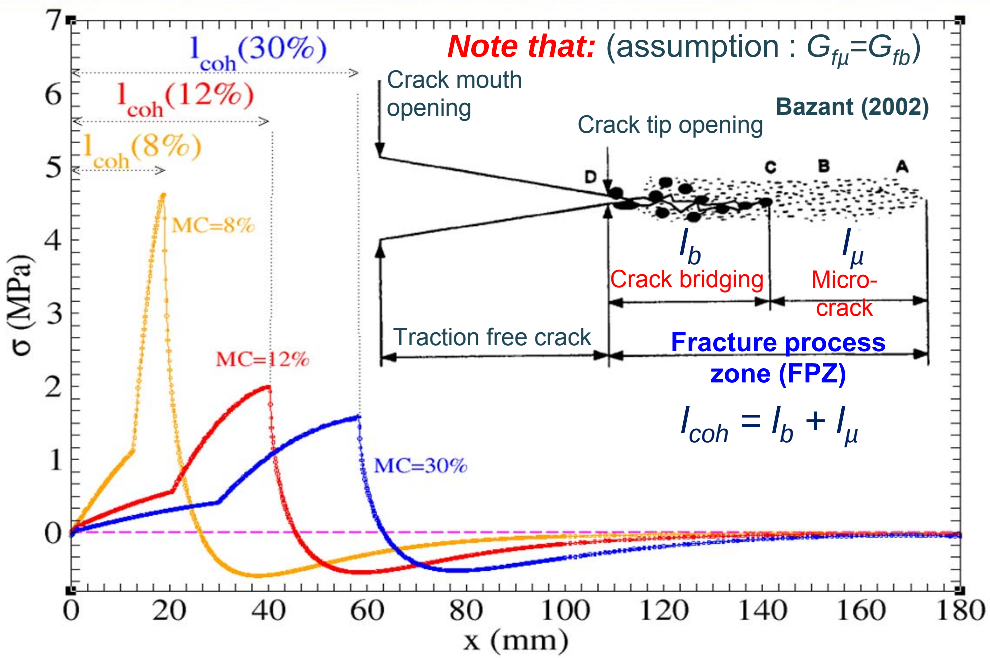


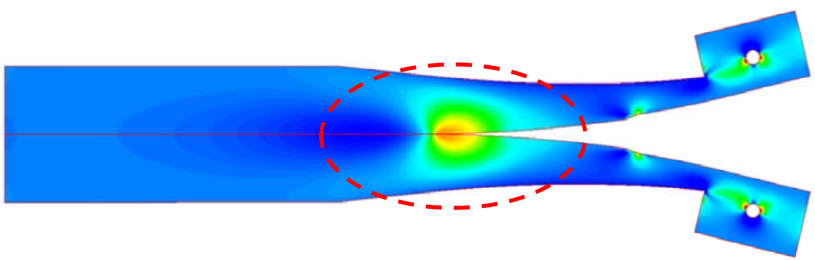

Step = 1050
Force (N)
Displacement (mm)
Normal stress (MPa)
Abscissa along the cohesive interface (mm)
Energy G_{coh} (J/m^2)
Crack length equivalent (mm)
Opening displacement (mm)
Abscissa along the cohesive interface (mm)
Stiffness K_i (N/mm)
Abscissa along the cohesive interface (mm)
Image FPZ (ratio)
Abscissa along the cohesive interface (mm)


Step = 900
Force (N)
Displacement (mm)
Normal stress (MPa)
Abscissa along the cohesive interface (mm)
Energy G_{coh} (J/m^2)
Crack length equivalent (mm)
Opening displacement (mm)
Abscissa along the cohesive interface (mm)
Stiffness K_I (N/mm)
Abscissa along the cohesive interface (mm)
Image FPZ (ratio)
Abscissa along the cohesive interface (mm)

Results : R-curve and parameters of CZM



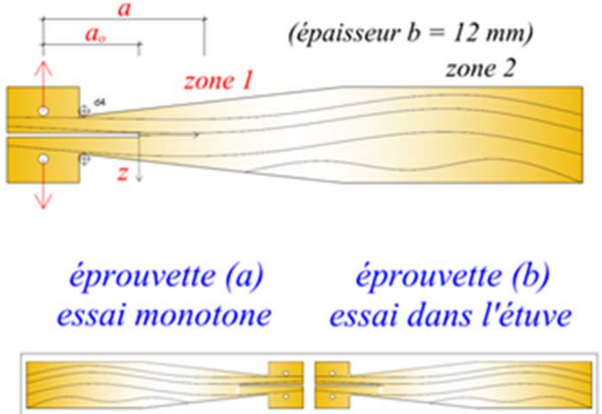


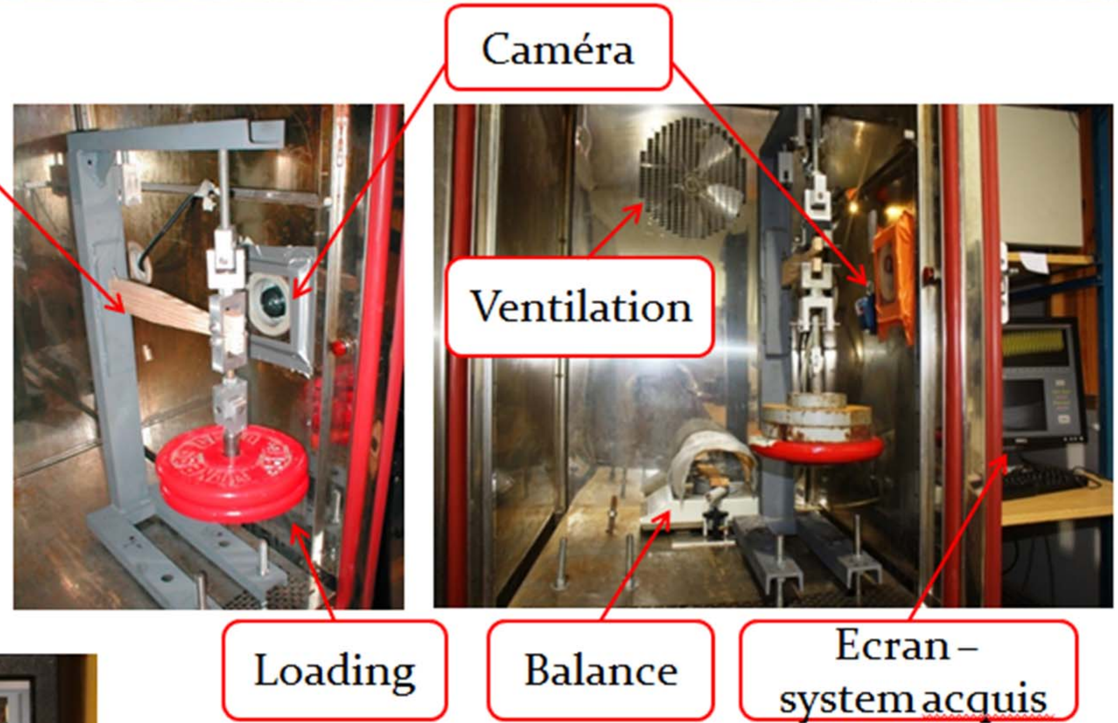


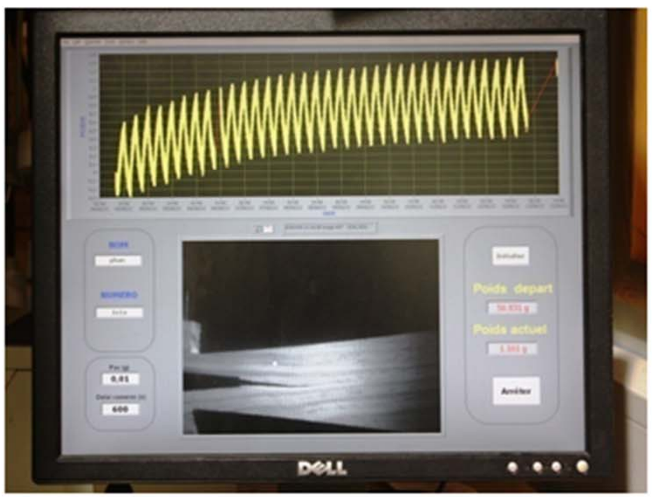
Stress field in the mTDCB specimen using CZM (FEA with Cast3m 2013)

Remarks :

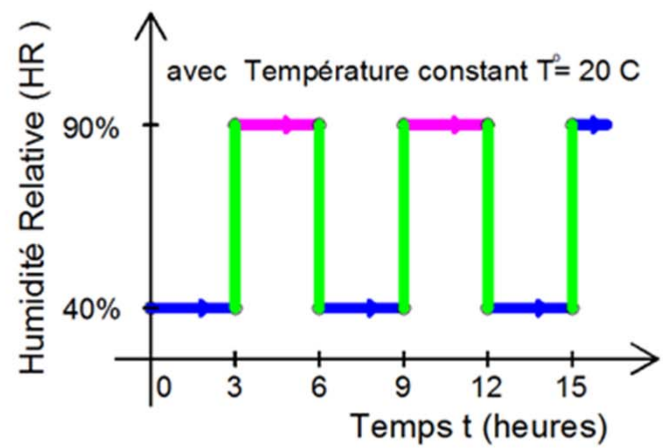
- ✓ Fracture properties (**R-curve, parameters of CZM**) depend on the moisture.
- ✓ ***G_{Rc}, l_{coh}*** increase with the increasing of MC.







Consigne:



Les images sont enregistré tous 5 minutes.

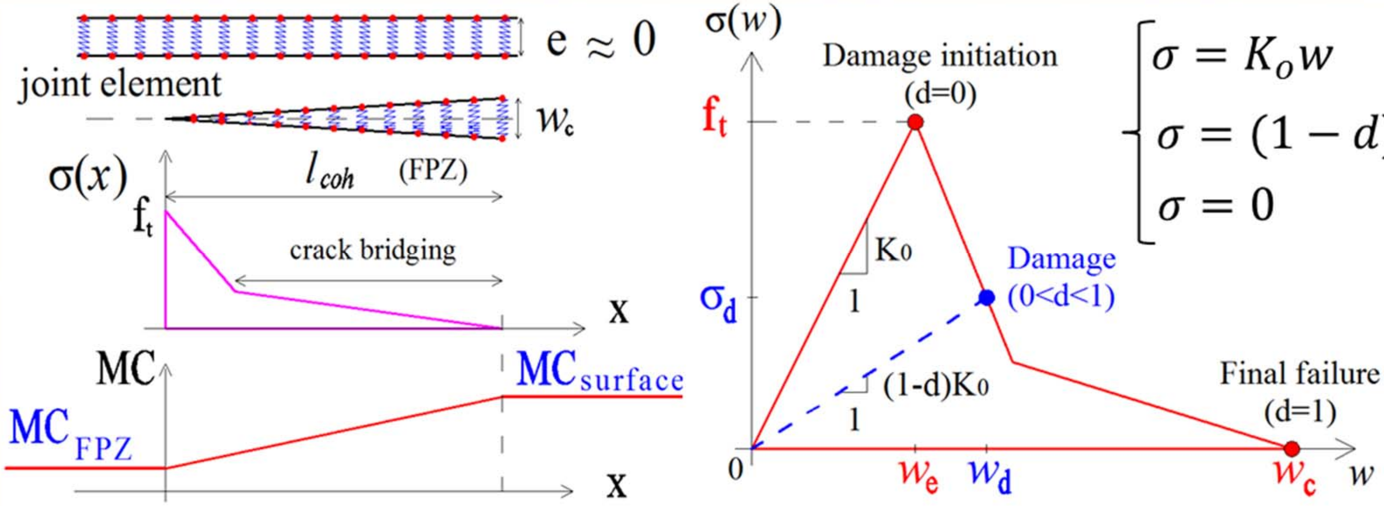
Moisture diffusion in wood

- The second Fick's law for diffusion:
  - $$\frac{\partial MC}{\partial t} = \frac{\partial}{\partial x}\left(D_{MC}(MC)\frac{\partial MC}{\partial x}\right)$$
  - $D^{\alpha}{}_{MC}(MC) = D_{\alpha}.e^{\kappa_0.MC}$ with $\alpha \in (L,R,T)$.

See Dubois *et al.* (2006, 2009, 2011, 2014)

- In this study, ***$MC_{surface}$*** (the equilibrium moisture) is changed to simulate the variation of relative humidity (RH).

Integration of rapid variation of *MC* in CZM



$$\begin{cases} \sigma = K_o w & if\ w \le w_e \\ \sigma = (1-d)\,K_o w & if\ w_e < w < w_c \\ \sigma = 0 & if\ w \ge w_c \end{cases}$$

$$d = \frac{w_d f_t - w_e \sigma_d}{w_d f_t}$$

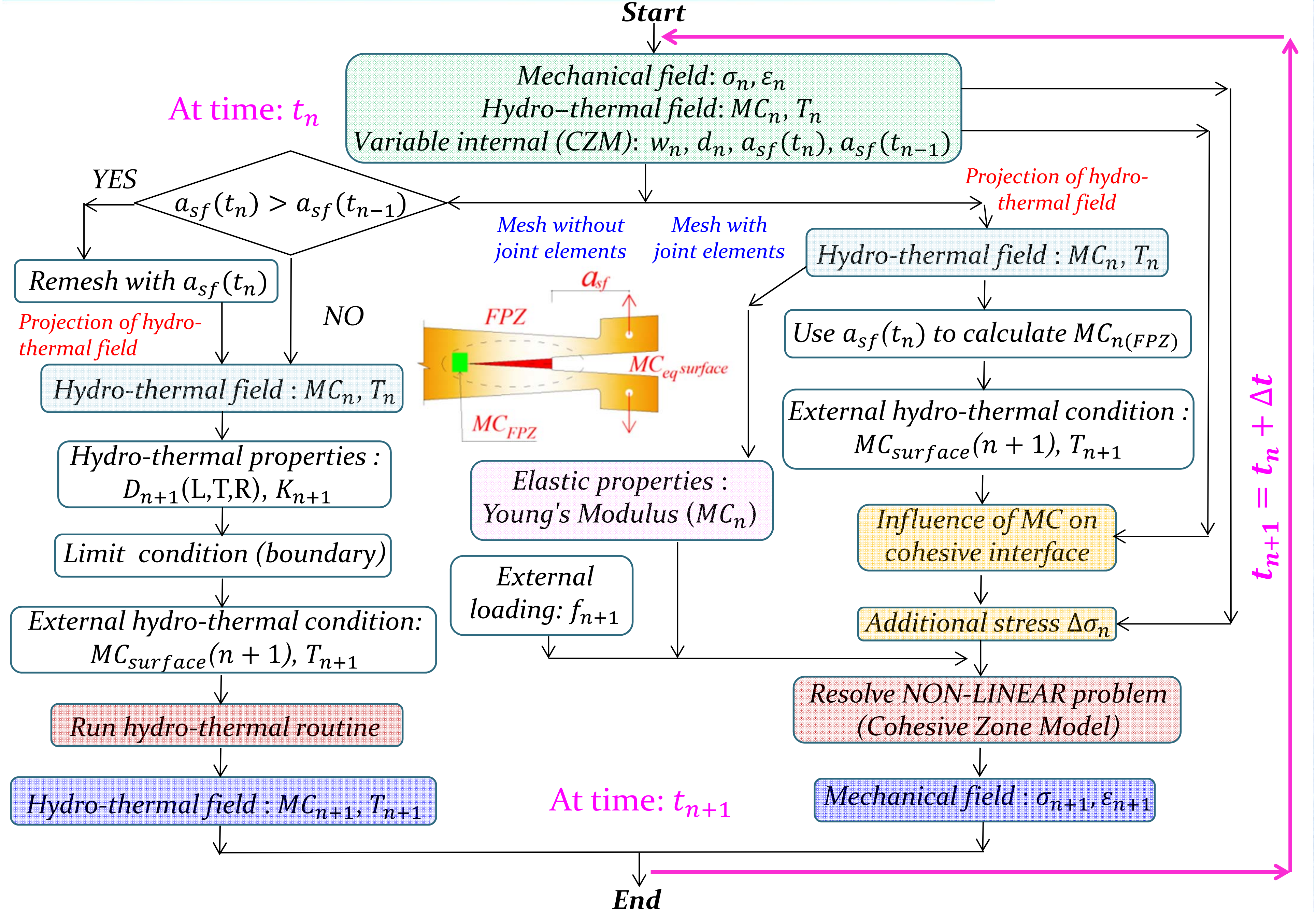
- The RH variation is rapid and has only a direct impact on fibers in the FPZ which is assumed to be **linear**.
- In the FE code, during the time increment Δt_n, the crack opening w is considered constant and the fictive stress σ^f_{n+1} is written as :

$$\begin{cases} \sigma_n = K_n w = \dfrac{E_0 f(MC_n,w)}{e}(1-d)w \\ \sigma^f_{n+1} = K_{n+1} w = \dfrac{E_0 f(MC_{n+1},w)}{e}(1-d)w \end{cases} \quad \text{with } w_e \le w \le w_c$$

$$\Delta\sigma_n = \sigma^f_{n+1} - \sigma_n$$

- $\Delta\sigma_n$ is converted into the **external mechanical nodal force increment** along the cohesive zone during Δt_n, translating incorporating the mechanical response history and the MC.

Moisture diffusion with crack growth algorithm



Our models

Cast3m 2013
version Développeur

My computer ▸ OS (C:) ▸ Cast3M ▸ PCW_13 ▸ bin

CSV	cmv_3d.eso	sau_kv.eso
EPS	coh_2d.eso	sau_rs.eso
ESOPE	coh_3d.eso	varint.eso
PROCEDUR	coml2.eso	yfxcmh.eso
bin_Cast3M_Win_32_13.exe	coml6m.eso	
bin_Cast3M_Win_64_13.exe	coml8m.eso	
bin_esope_Win_32_13.exe	cotraj.eso	
bin_esope_Win_64_13.exe	cotype.eso	
cast_64_13.exe	dsigef.eso	
ftnchek_331_13.exe	elas_h.eso	
parameter_input	elas_s.eso	
UTILNOTI	fkelvi.eso	
UTILPROC	flu_am.eso	
fort.3	flu_kv.eso	
cast_UTIL13.bat	flu_rs.eso	
castem13.bat	idflua.eso	
compil_tout_cast13.bat	idplas.eso	
compilcast13.bat	idvari.eso	
compilcast13_0.bat	kelvoi.eso	
compilcast13_d.bat	modflu.eso	
essaicast13.bat	modpla.eso	
Move_file_bin_Castem.bat	nomate.eso	
calflu.eso	sau_am.eso	
cmv_2d.eso	sau_fl.eso	

30 files .ESO

```
C NOMATE      SOURCE     BR232186  12/08/01     22:29:16      7456
      SUBROUTINE NOMATE(FORMOD,NFOR,MATMOD,NMAT,CMATE,IMATE,INATU)
      IMPLICIT INTEGER(I-N)
      IMPLICIT REAL*8 (A-H,O-Z)
*  le dernier numero de materiau utilise est le    :     160
*-----------------------------------------------------------------------*
```

*C:\Cast3M\PCW_13\bin\coml8m.eso

Fichier Édition Recherche Affichage Encodage Langage Paramétrage Macro Exécution Compléme

coml8m.eso

```
 1296 continue
      endif
 1295 continue
      if(INPLAS.GE.161) THEN

C        modele   I2M_GCE_KELVIN_VOIGT
         if(INPLAS.EQ.161) go to 461

C        modele   I2M_GCE_MECANOSORPTION
         if(INPLAS.EQ.162) go to 462

C        modele   I2M_GCE_MAXWELL
         if(INPLAS.EQ.163) go to 463

C        modele   I2M_GCE_COHESIF
         if(INPLAS.EQ.164) go to 464

C        modele   I2M_GCE_COHESIF_VISCOELASTIC
         if(INPLAS.EQ.165) go to 465
      else
         go to 900
      end if
C
```

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Université de Bordeaux, I2M/Dépt. GCE
Email : na.phan@i2m.u-bordeaux1.fr

université de BORDEAUX

I2M BORDEAUX

Comparison with JOINT-SOFT model


```
**********************************************************************
* Les paramètres pour le matériaux *
**********************************************************************
*
****** JOINT SOFT   **************************************************
MO_JOIN = MODL INTERFAC MECANIQUE ELASTIQUE PLASTIQUE
'JOINT_SOFT' JOI4;
MA_JOIN = MATE MO_JOIN 'KS' (mTDCB.'KS_join') 'KN' (mTDCB.'KN_join')
'SJTB' (mTDCB.'EVOL_Trac_Ouv') 'SJCB' COMP_FER 'SJSB' CISa_GLI;
```

JOINT-SOFT model

MATE.notice (http://www-cast3m.cea.fr/index.php?page=notices&notice=MATE)

```

    Modele JOINT_SOFT
    ---------------------
      Il s'agit d'un modele de joint avec un critere de Mohr-Coulomb
      et avec adoucissement en traction et cisaillement. L'ecoulement se
      fait sans dilatance.

    'PNOR'     : Position de la pointe (hypothetique) du cone
    'SJTB'     : Relation contrainte normale - ouverture du joint en traction
                (type EVOLUTION - Valeur positive pour la traction)
    'SJCB'     : Relation contrainte normale - fermeture du joint en traction
                (type EVOLUTION - Valeur positive pour la traction)
    'SJSB'     : Relation contrainte de cisaillement - glissement en cisaillement
                 pour une contrainte normale nulle (Type EVOLUTION)
    'BETA'     : Parametre controlant la decharge en cisaillement
    'CPLG'     : Definition des couplages

```

Comparison with JOINT-SOFT model


```
**********************************************************************
* Les paramètres pour le matériaux *
**********************************************************************
*
****** JOINT SOFT   **************************************************
MO_JOIN = MODL INTERFAC MECANIQUE ELASTIQUE PLASTIQUE
'JOINT_SOFT' JOI4;
MA_JOIN = MATE MO_JOIN 'KS' (mTDCB.'KS_join') 'KN' (mTDCB.'KN_join')
'SJTB' (mTDCB.'EVOL_Trac_Ouv') 'SJCB' COMP_FER 'SJSB' CISa_GLI;
```

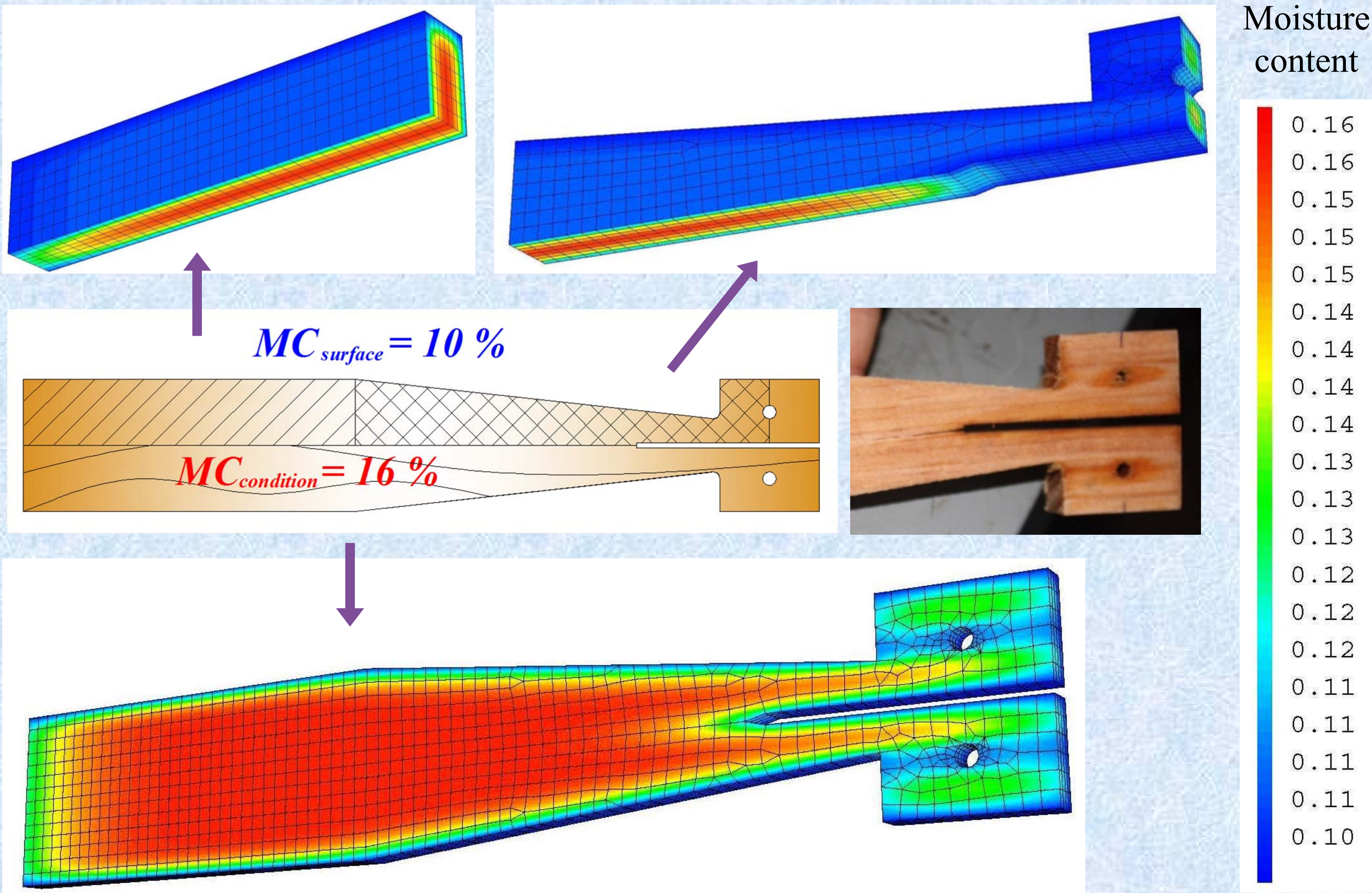
JOINT-SOFT model

```
****** JOINT COHESIVE  ***********************************************
MO_JOIN = MODL INTERFAC MECANIQUE ELASTIQUE PLASTIQUE
'I2M_GCE_COHESIF_VISCOELASTIC' JOI4;
MA_JOIN = MATE MO_JOIN 'KS' (mTDCB.'KS_join') 'KN' (mTDCB.'KN_join')
'STL' (mTDCB.'EVOL_Trac_Ouv') 'MC_i' 0.15 'MC_s' 0.13;
*
****** BOIS: VISCO-ELASTIC ORTHOTROPE  *******************************
*
SI mTDCB.'Bois_viscoelastique';
MOBOIS = MODE VOLTOTAL MECANIQUE ELASTIQUE ORTHOTROPE
'FLUAGE' 'I2M_GCE_KELVIN_VOIGT';
MABOIS = VIS_BOIS mTDCB MOBOIS;
SINON;
MOBOIS = MODE VOLTOTAL MECANIQUE ELASTIQUE ORTHOTROPE;
MABOIS = MAT_BOIS mTDCB MOBOIS;
FINSI;
```

Our CZM model

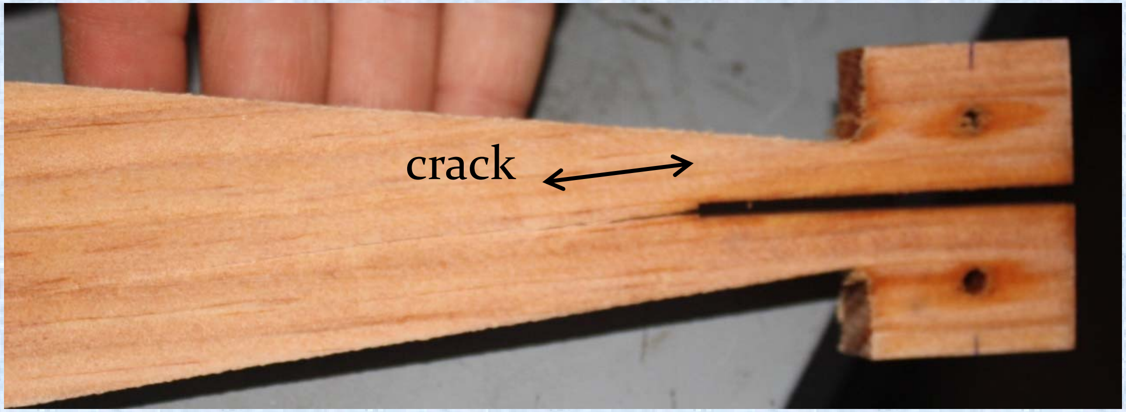
- 3 parameters
- Updated in PERSO1, PASAPAS

Results : Evolution of the moisture content

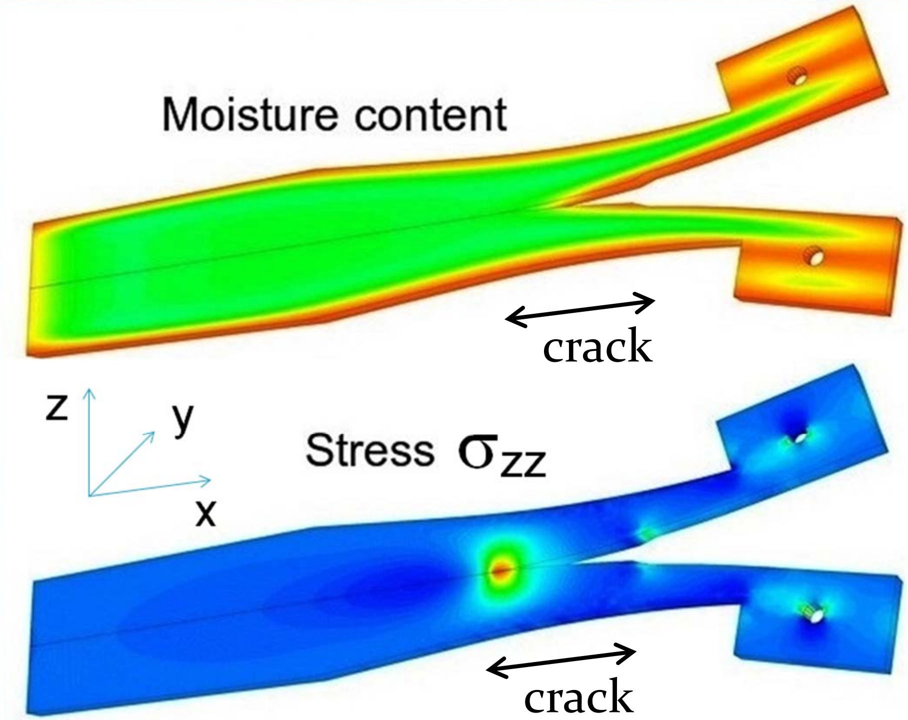


Time diffusion : 120 min

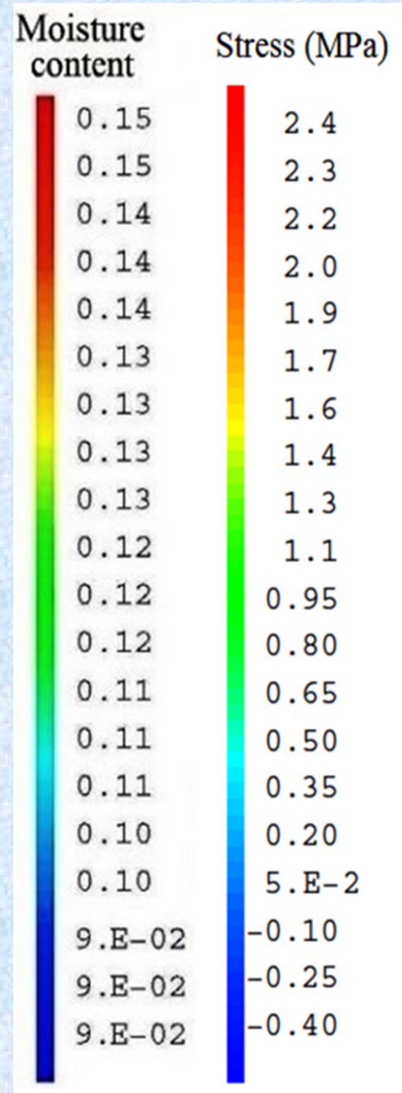
Results : moisture diffusion + crack growth



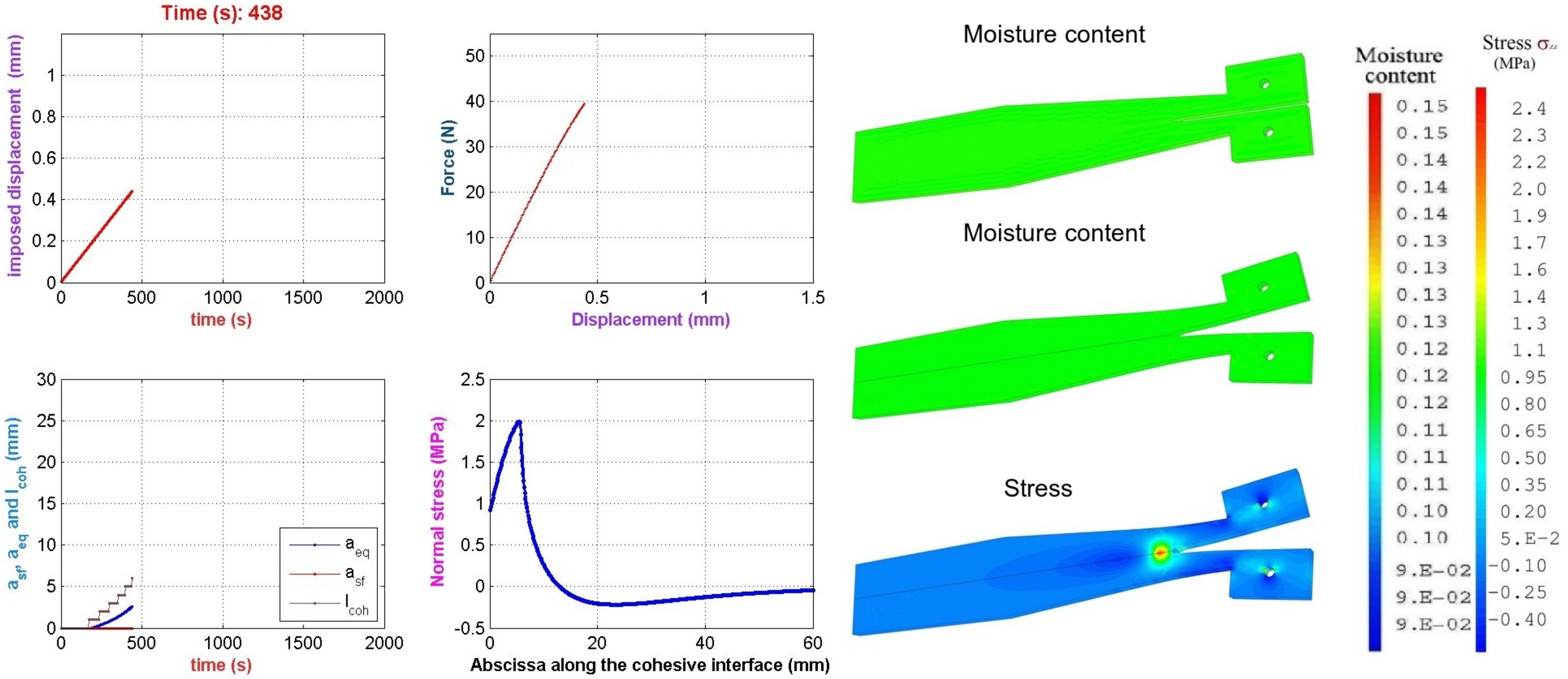
Middle section of the mTDCB specimen



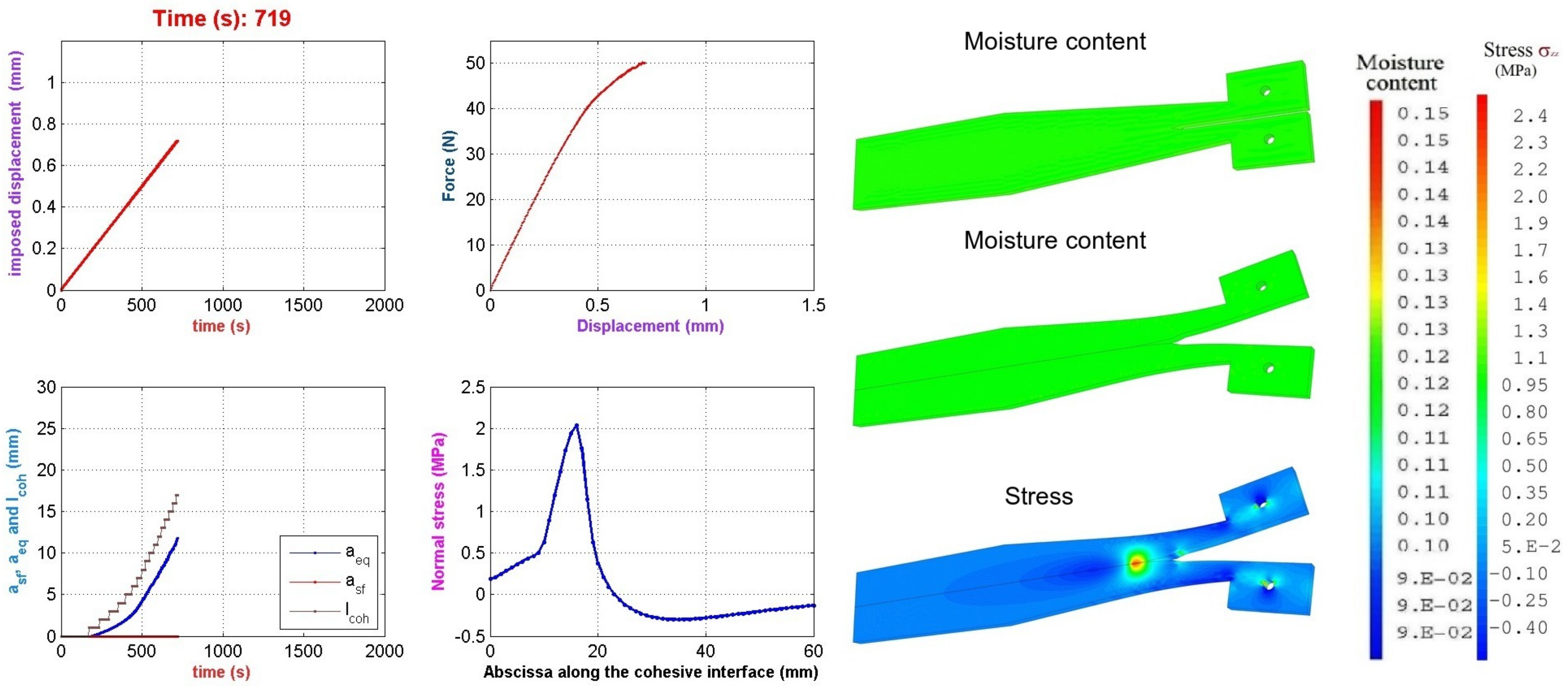
Stress and deformation of mTDCB specimen
(Deformation scale : 5.)



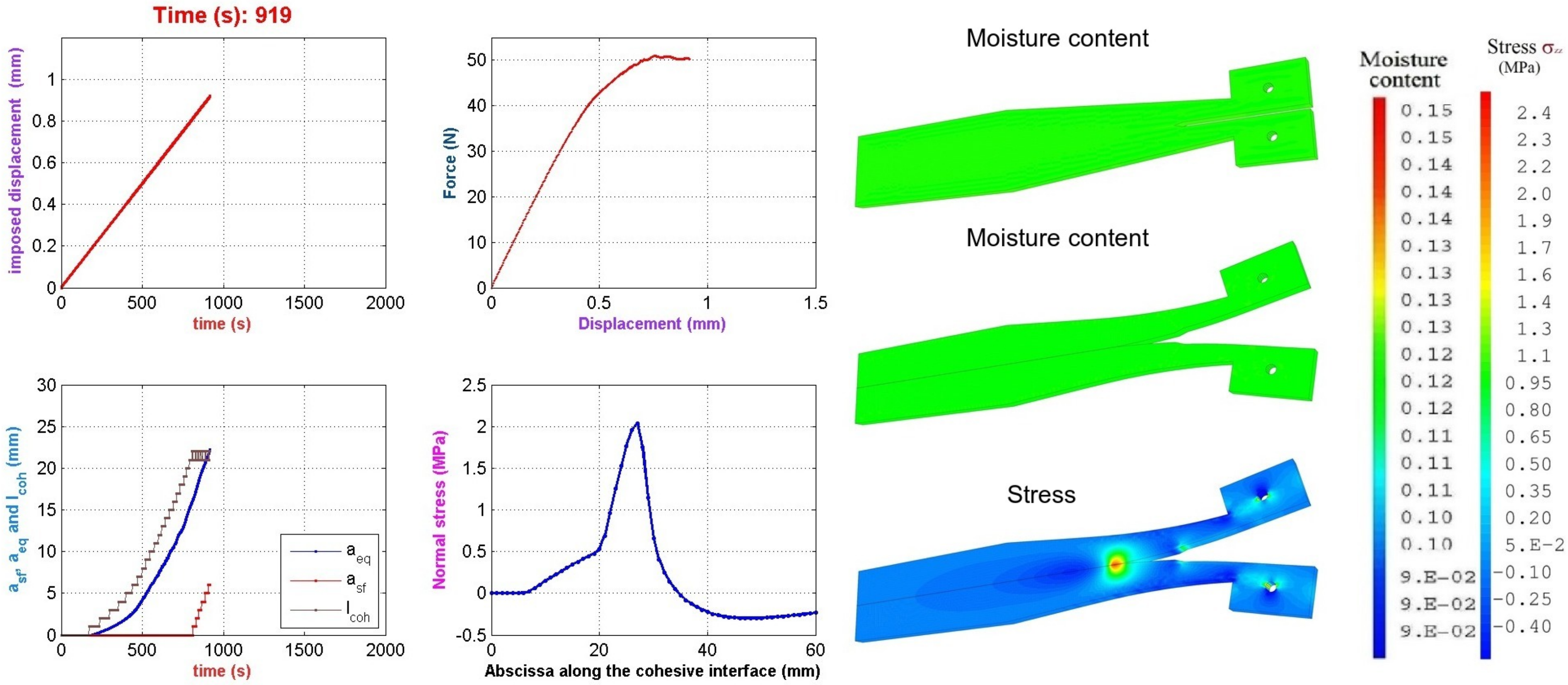
ELEM : CUB8
NBNO : 72850
NBEL : 64440
Memory : 24Gb
Calculation time : 240 h
→ Cluster Avakas MCIA



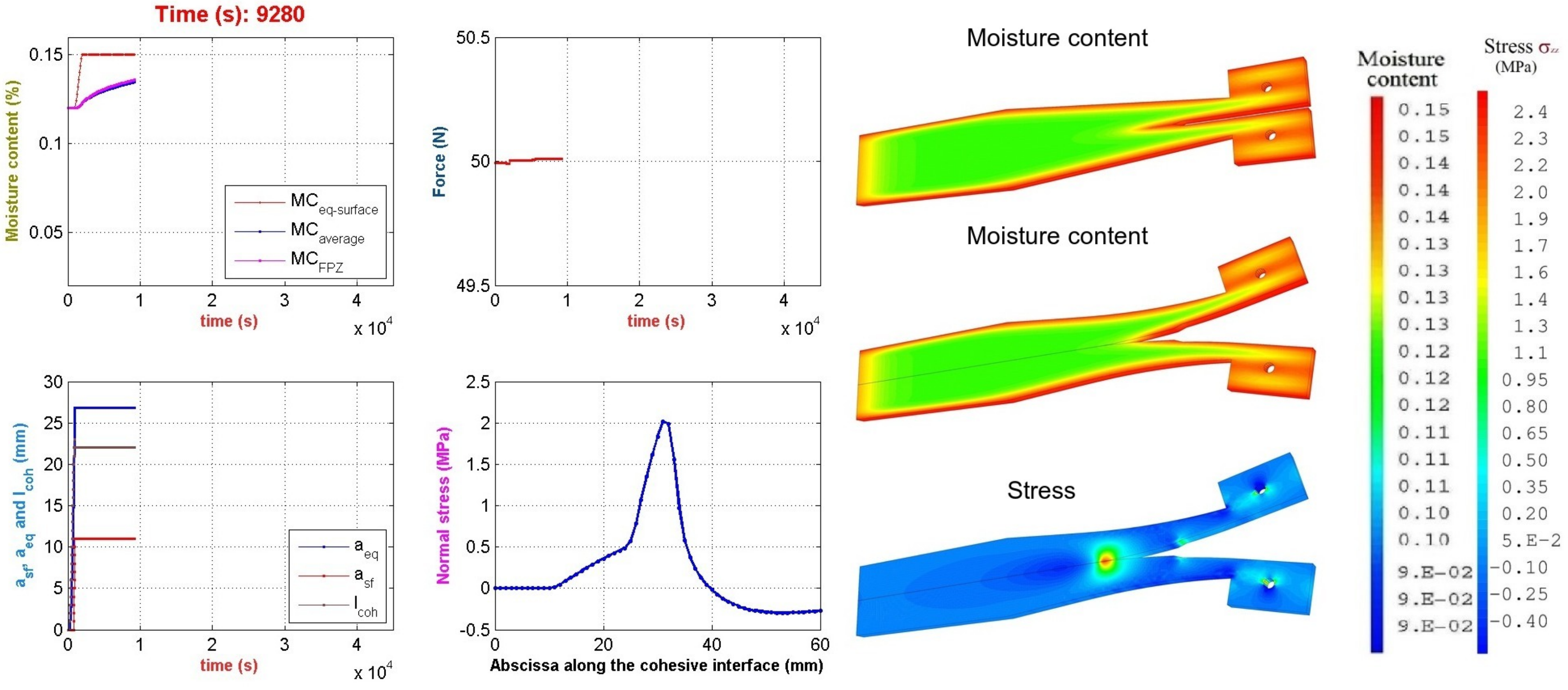
Time (s): 438
imposed displacement (mm)
time (s)
Force (N)
Displacement (mm)
a_{sf}, a_{eq} and l_{coh} (mm)
a_{eq}
a_{sf}
l_{coh}
time (s)
Normal stress (MPa)
Abscissa along the cohesive interface (mm)
Moisture content
Moisture content
Stress
Moisture content
0.15 0.15 0.14 0.14 0.14 0.13 0.13 0.13 0.13 0.12 0.12 0.12 0.11 0.11 0.11 0.10 0.10 9.E-02 9.E-02 9.E-02
Stress σ_{zz} (MPa)
2.4 2.3 2.2 2.0 1.9 1.7 1.6 1.4 1.3 1.1 0.95 0.80 0.65 0.50 0.35 0.20 5.E-2 -0.10 -0.25 -0.40



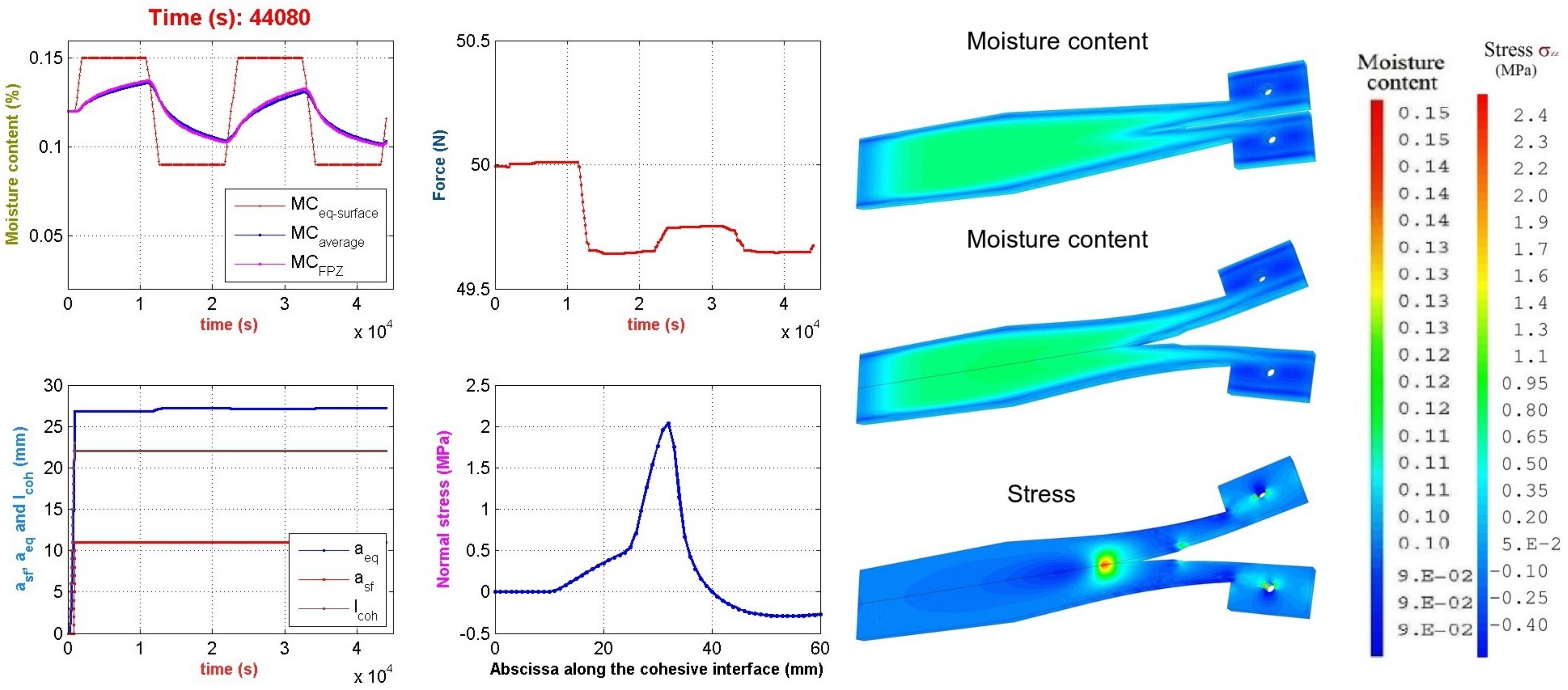
Time (s): 719
imposed displacement (mm)
time (s)
Force (N)
Displacement (mm)
a_{sf}, a_{eq} and l_{coh} (mm)
a_{eq}
a_{sf}
l_{coh}
time (s)
Normal stress (MPa)
Abscissa along the cohesive interface (mm)
Moisture content
Moisture content
Stress
Moisture content
Stress σ_{zz} (MPa)



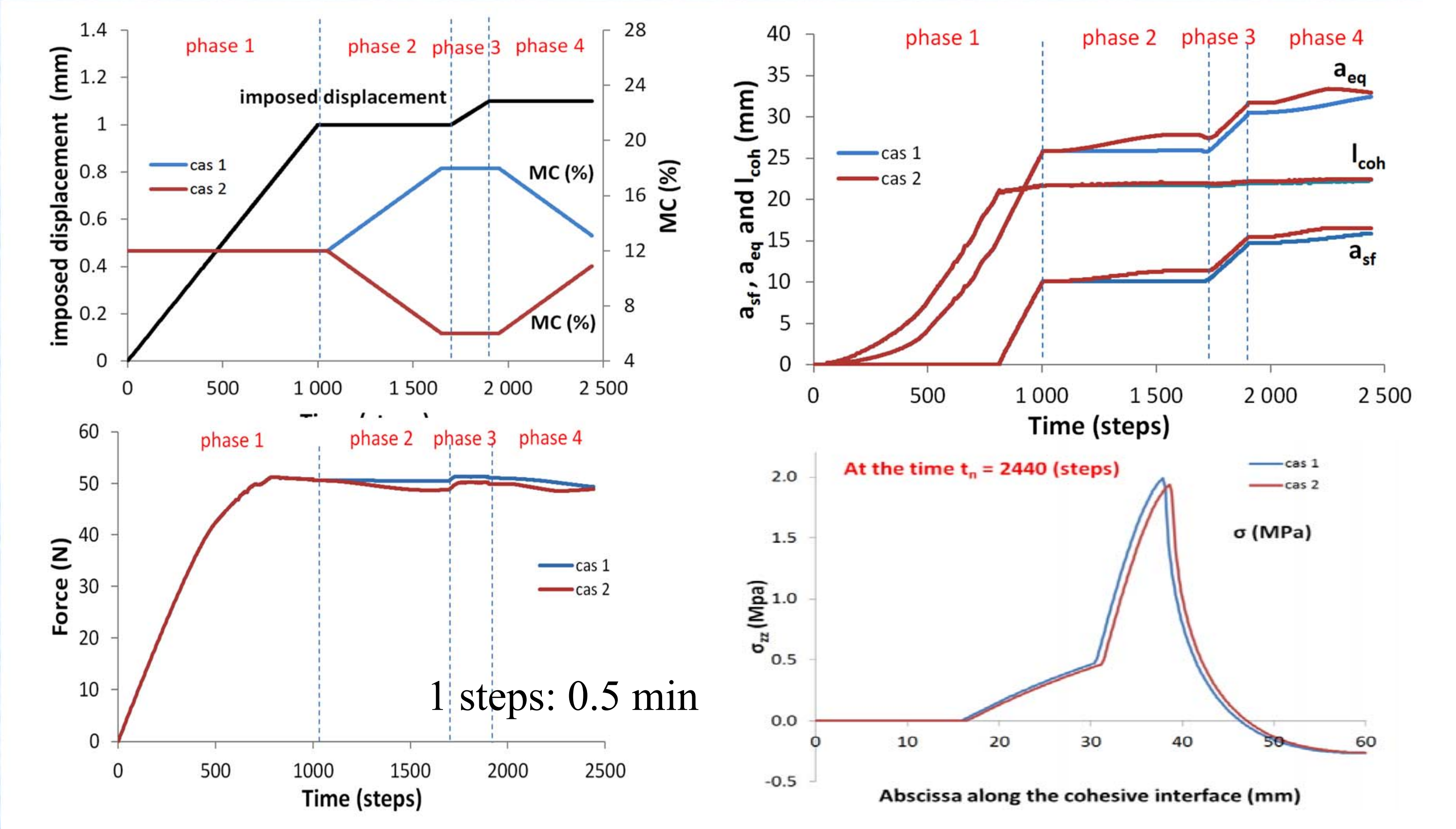
Time (s): 919
imposed displacement (mm)
time (s)
Force (N)
Displacement (mm)
a_sf, a_eq and l_coh (mm)
a_eq
a_sf
l_coh
time (s)
Normal stress (MPa)
Abscissa along the cohesive interface (mm)
Moisture content
Moisture content
Stress
Moisture content
Stress σzz (MPa)



Time (s): 9280
Moisture content (%)
MCeq-surface
MCaverage
MCFPZ
time (s)
x 10^4
Force (N)
asf, aeq and lcoh (mm)
aeq
asf
lcoh
Normal stress (MPa)
Abscissa along the cohesive interface (mm)
Moisture content
Moisture content
Stress
Moisture content
Stress σzz (MPa)


Time (s): 44080
Moisture content (%)
time (s)
x 10^4
MC eq-surface
MC average
MC FPZ
Force (N)
time (s)
x 10^4
a sf, a eq and l coh (mm)
time (s)
x 10^4
a eq
a sf
l coh
Normal stress (MPa)
Abscissa along the cohesive interface (mm)
Moisture content
Moisture content
Stress
Moisture content
Stress σzz (MPa)

Results : Moisture diffusion + crack growth



- In the wetting process while the imposed displacement is constant (phase 2), the stiffness decreases leading to reduced stress in the cohesive zone. The crack tends to be closed and the applied force tends to increase (crack does not further develop).
- All phenomena are converse in case of the drying phases.
- **Phase 3** is continued with the increasing imposed displacement and constant moisture. We observe **a continuity of the mechanical response** which takes into account all previous changes.

- In this research, a new model, which integrates MC influences on the cohesive zone, is proposed and implanted in Cast3m.
- In further studies, this model will be analyzed with the moisture diffusion inside the whole specimen which results in viscoelasticity variation.

Thank you for your attention!

Projet VS2C :