7th Mfront User Day

Development of a Novel Damage Model for Concrete Subjected to Creep

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R&D UK Centre

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19/10/2021

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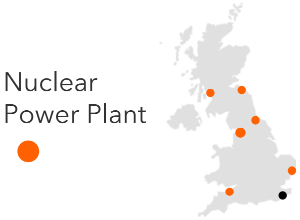
1.Industrial and Project Context

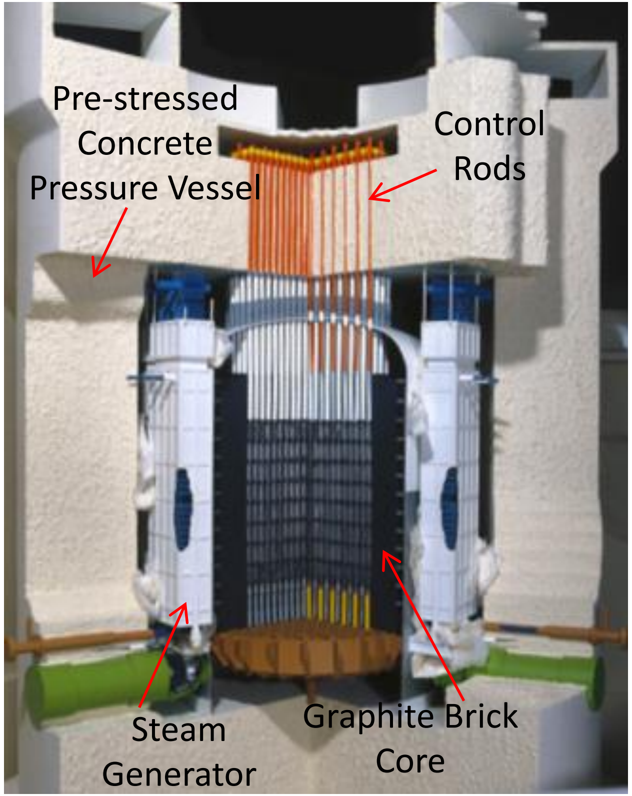


7
nuclear power stations in UK
Online: **12 AGRs, 1 PWR**
Offline: **2 AGR**

Targeting Concrete pressure vessels:
- Safety assesment during LOCA
- In-service life assessments (30+ years of operations)
- Decommissioned (awaiting defueling)

Exisiting models (in Mfront) :
- LITS (standalone),
- Damage (standalone),
- LITS+Damage (coupled)

Objective :
- Highlighting the formation of cracks and assessing their effects on concrete vessels – *from cradle to grave*.
- Accounting for high temperature including Load Induced Thermal Strain (LITS) phenomenon and long-term creep



1.Industrial and Project Context

Project Context

complexity →

SMiRT-25

LITS
- Confinement-dependant LITS model for T<500°
- Moisture-dependent LITS model
- Axisymmetric model (HPB)

FLB
- FLB model in MFront
- Benchmark with other damage models in Mfront

FLB-LITS
- FLB-LITS model in MFront
- V&V on 2D (stress plane, cycling test)

Creep
- Creep model in MFront
- V&V on 2D/3D

Creep-FLB
- Creep-FLB model in MFront
- V&V on 3D

Creep-FLB-LITS
- FLB-LITS-Creep model in MFront
- V&V on 2D

2014 2018 2019 2020 2021

Thesis — *EDF Energy R&D Project*

2th MFront User Day

https://github.com/thelfer/tfel-doc/blob/master/MFrontUserDays/SecondUserDay/torelli-lits.pdf
https://github.com/thelfer/MFrontGallery/blob/master/generic-behaviours/viscoplasticity/LoadInducedThermalStrain_Torelli2018.mfront

http://tfel.sourceforge.net/FichantLaBorderieDamageBehaviour.html
https://github.com/thelfer/MFrontGallery/blob/master/generic-behaviours/damage/FichantLaborderieDamageBehaviour.mfront

2 . The damage Model

Isotropric Damage Model

Use of an **Isotropic Damage model** applied to quasi-brittle material such as concrete

Damage models have the ability to numerically :

- **initiate** crack(s)
- **propagate** crack(s)

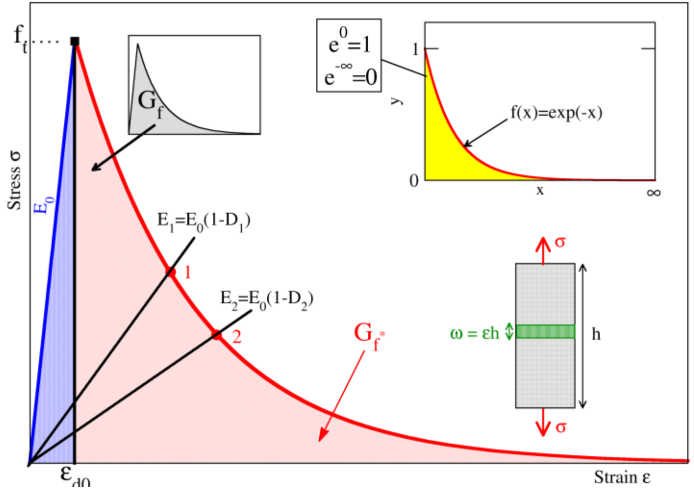
Concrete damage models should take into account :

- **Asymmetry** between tensile and compressive behaviour
- **Unilateral Effect** (also called crack closure effect)
- **Independency of the mesh** density/size

Fichant-La Borderie (FLB)

*(extension of the well known **Mazars** model)*

- **Variable scalar damage** *D* (if *D~1* it is a crack, if *D=0* sane material)
- **Local damage model** with an energetic regularisation method
- Unilateral effect based on the stress tensor
- Can be coupled with plasticity (*Matallah,2009*)[1] and/or creep (*Saliba, 2013*)[2]
- Support mesoscopic scale (aggregates, rebar…)



[1] Matallah, M., La Borderie, C., 2009. *Inelasticity-damage-based model for numerical modeling of concrete cracking*. Engineering Fracture Mechanics 76, 1087–1108.

[2] Saliba, J. *et al*. (2013). *Relevance of a mesoscopic modeling for the coupling between creep and damage in concrete*. Mechanics of Time-Dependent Materials, 17(3):481–499.

2 . The damage Model : Fichant – La Borderie

FLB : Theory

1- No *visco-elasticity-plasticity* in decomposition of strains

$$\varepsilon_{ij}^{tot} = \varepsilon_{ij}^{el} \qquad \text{tensor}$$

2- Damage occurs on elastic strains part when $\varepsilon_{eq} > \varepsilon_{d0}$

$$\varepsilon_{eq} = \sqrt{\sum_{i=1}^{3} \langle \varepsilon_{ij}^{el} \rangle_{+}^{2}} \quad > \quad \varepsilon_{d0} = \frac{f_t}{E} \qquad \text{scalar}$$

3- Computation of the damage (exponential law)

$$D = 1 - \frac{\varepsilon_{d0}}{\varepsilon_{eq}} exp\left(B_t\left(\varepsilon_{d0} - \varepsilon_{eq}\right)\right) \qquad \text{scalar}$$

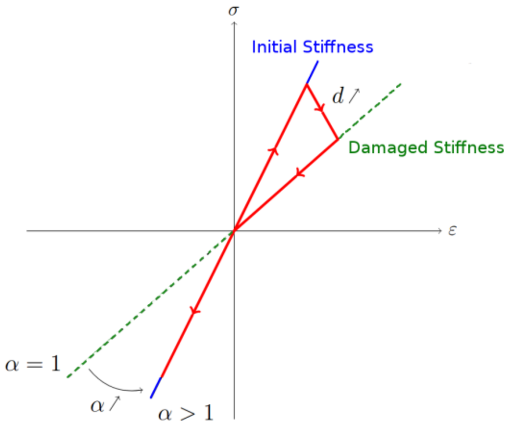
$$B_t = \frac{f_t h}{G_f - 0.5\varepsilon_{d0} f_t h}$$

4- Computation of total final stress tensor (damaged one) - Unilateral effect (crack closure)

$$\sigma_{ij}^{tot} = \underbrace{(1 - D)\langle\tilde{\sigma}_{ij}\rangle_{+}}_{\textit{Tensile State}} + \underbrace{(1 - D^{\alpha})\langle\tilde{\sigma}_{ij}\rangle_{-}}_{\textit{Compressive State}} \qquad \text{tensor}$$

$$\tilde{\sigma}_{ij} = E_{ijkl}^{0} : \varepsilon_{ij}^{el}$$

- **2 Elastic parameters :**
- Young Modulus (E),
- Poisson's ratio (ν),
- **3 Fracture parameters :**
- Fracture Energy (G_f),
- Tensile strength (f_t),
- Participation of the damage in compression (α),
- **1 Finite element parameter :**
- Average element size at the Gauss Point (h).



$\boldsymbol{\alpha}$: Factor linked to the damage in compressive state (Material Parameter)

- $\boldsymbol{\alpha = 1}$ **:** *no unilateral effect – same damage in compression and tension*
- $\boldsymbol{1 < \alpha < 1000}$ **:** *effect on the level of the damage for the stiffness recovery*
- $\boldsymbol{\alpha > 1000}$ **:** *no damage in compression*

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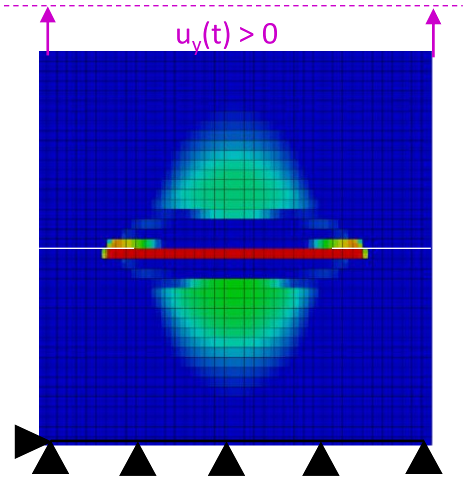
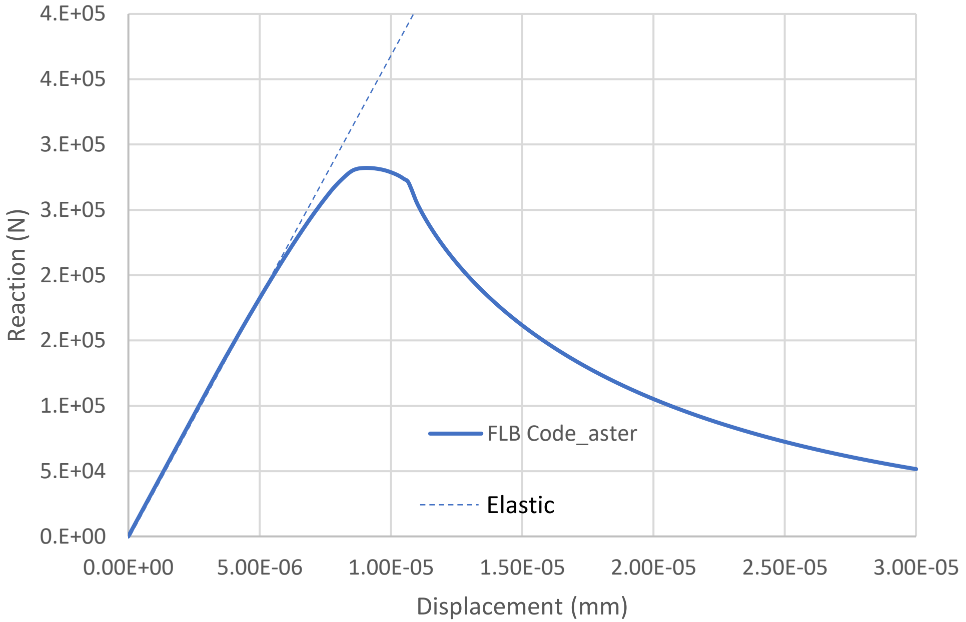
2 . The damage Model : Fichant – La Borderie

FLB : Damage Field

Example REV : 10x10 cm (Strain Plan)



Damage field



Macroscopic Response

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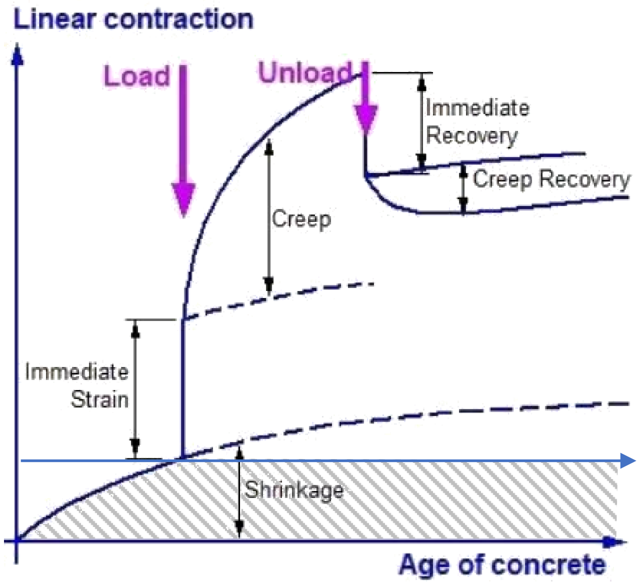
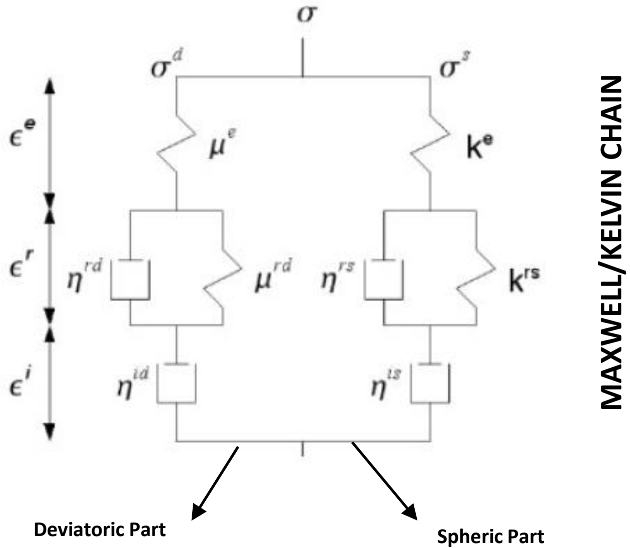
3 . The basic Creep Model : Burger

Basic Creep : Burger Model



Elastic and creep deformation of mass concrete under constant load followed by load removal

BETON_BURGER
[R7.01.35]



- Started point : **BurgerAgeing.mfront**

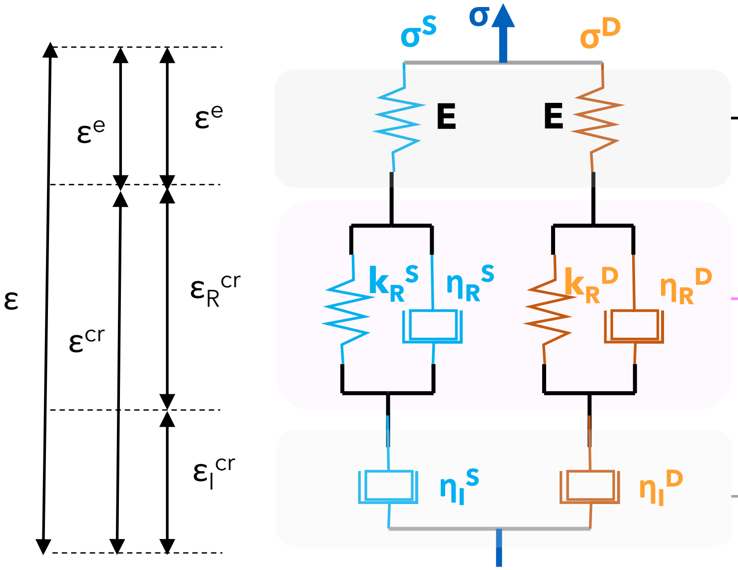
From verification code_aster test case mfron02c

Drying Creep has been removed

3 . The basic Creep Model : Burger

Basic Creep : Burger Model

$\sigma = \sigma^S + \sigma^D$



→ Elastic (E, ν)

→ Basic creep Recovery

→ Irreversible basic creep

- **6 Creep parameters :**

$$\frac{k_R^S}{k_R^D} = \frac{\eta_R^S}{\eta_R^D} = \frac{\eta_I^S}{\eta_I^D} = \frac{(1+\nu)}{(1-2\nu)}$$

→ Bulk modulus $k_R^S = \dfrac{E}{3(1-2\nu)}$

η : viscosity (Pa.s)
k : rigidity (Pa)

- **Creep parameters are dependant to the temperature:**

Thermal Factor

$$\times\ (T_0)\, e^{\frac{E_{ac}}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

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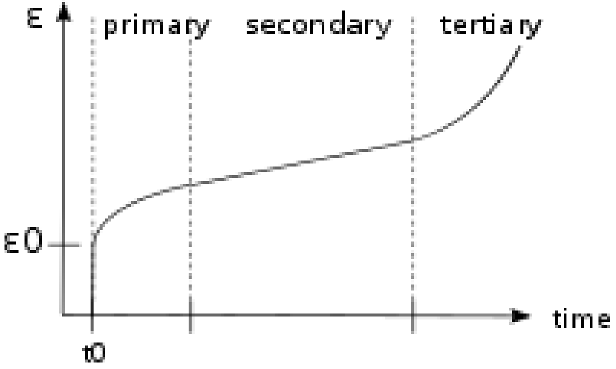
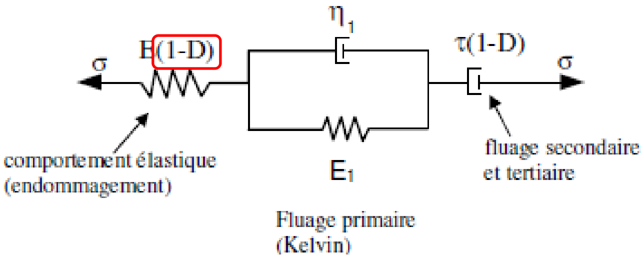
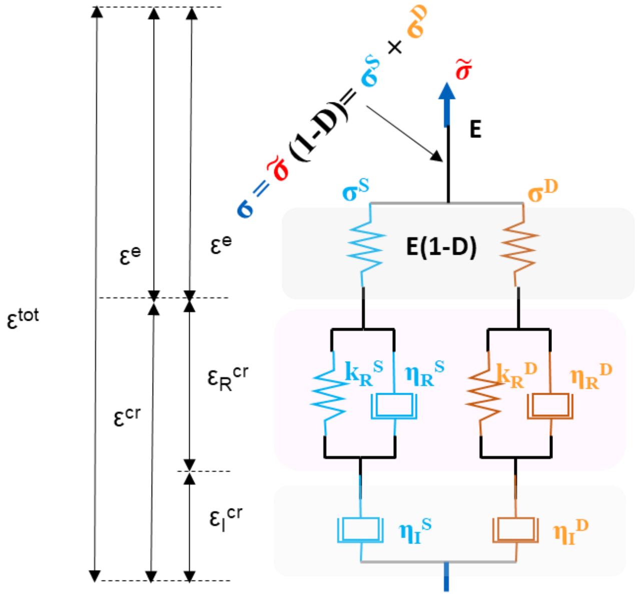
4 . Coupling Damage and Creep

Burger-FLB Model

Introduction to damage







Introduction of a coupling Parameter : β

$$\varepsilon_{eq} = \sqrt{\sum_{i=1}^{3} \left\langle \varepsilon_{ij}^{ela,0} \right\rangle_+^2 + \boldsymbol{\beta} \sum_{i=1}^{3} \left\langle \varepsilon_{ij}^{creep} \right\rangle_+^2}$$

4 . Coupling Damage and Creep

Burger-FLB Model : a visco-elasto-damage model

$$\varepsilon_{tot} = \varepsilon_{ela,0} + \varepsilon_{ij}^{creep}$$

1- *Computation of the effective stress* $\tilde{\sigma}_{ij}$ under Mechanic and Thermal solicitation

BURGER

2 - Computation of Creep strain ε_{ij}^{creep} based on deviatoric and spheric part of the *the effective stress*

$$\rightarrow \varepsilon_{ij}^{creep} = \varepsilon_R^S + \varepsilon_I^S + \varepsilon_R^D + \varepsilon_I^D$$

3 - Computation of elastic strain ε_{ij}^{elas}

4 - Computation of equivalent strain ε_{eq}

β : effect of creep on the damage

$$\rightarrow \varepsilon_{eq} = \sqrt{\sum_{i=1}^{3} \left\langle \varepsilon_{ij}^{ela,0} \right\rangle_+^2 + \boldsymbol{\beta} \sum_{i=1}^{3} \left\langle \varepsilon_{ij}^{creep} \right\rangle_+^2}$$

FLB

5- Estimation of potential damage D

$$\rightarrow D = 1 - \frac{\varepsilon_{d0}}{\varepsilon_{eq=f(\varepsilon_{ela,0})}} exp\left(B_t\left(\varepsilon_{d0} - \varepsilon_{eq=f(\varepsilon_{ela,0})}\right)\right)$$

6- Computation of final stress σ_{ij}

$$\rightarrow \sigma_{ij} = (1 - D)\langle\tilde{\sigma}_{ij}\rangle_+ + (1 - D^{\alpha})\langle\tilde{\sigma}_{ij}\rangle_-$$

$$\tilde{\sigma}_{ij} = E_{ijkl} : \varepsilon_{kl}^{ela,0}$$

7- Updating the effective stress $\tilde{\sigma}_{ij=f(\varepsilon_{ela,0})}$ that contains now the creep effect (ε_{ij}^{creep})

8- Updating the final damage D that contains now creep effects (ε_{ij}^{creep})

BURGER + FLB

9- Updating the final stress tensor $\sigma_{ij}(D, \varepsilon_{kl}^{ela,0}, \varepsilon_{ij}^{creep})$

4 . Coupling Damage and Creep

Internal Variable (3D case)

• first component of internal variable 'ElasticStrain'
• second component of internal variable 'ElasticStrain'
• third component of internal variable 'ElasticStrain'
• fourth component of internal variable 'ElasticStrain'
• fifth component of internal variable 'ElasticStrain'
• sixth component of internal variable 'ElasticStrain'
• Reversible_SphericalStrain
• Irreversible_SphericalStrain
• first component of internal variable 'Reversible_DeviatoricStrain'
• second component of internal variable 'Reversible_DeviatoricStrain'
• third component of internal variable 'Reversible_DeviatoricStrain'
• fourth component of internal variable 'Reversible_DeviatoricStrain'
• fifth component of internal variable 'Reversible_DeviatoricStrain'
• sixth component of internal variable 'Reversible_DeviatoricStrain'
• first component of internal variable 'Irreversible_DeviatoricStrain'
• second component of internal variable 'Irreversible_DeviatoricStrain'
• third component of internal variable 'Irreversible_DeviatoricStrain'
• fourth component of internal variable 'Irreversible_DeviatoricStrain'
• fifth component of internal variable 'Irreversible_DeviatoricStrain'
• sixth component of internal variable 'Irreversible_DeviatoricStrain'
• Damage

• first component of internal variable 'CreepStrain'
• second component of internal variable 'CreepStrain'
• third component of internal variable 'CreepStrain'
• fourth component of internal variable 'CreepStrain'
• fifth component of internal variable 'CreepStrain'
• sixth component of internal variable 'CreepStrain'
• Epsi_eq

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4 . Coupling Damage and Creep

Quick View on the Mfront file

```
@Parser Implicit;
@Behaviour burger_flb;
@Algorithm NewtonRaphson_NumericalJacobian;
@Theta 1.;
@Epsilon 1.E-11;
```

```
@InitLocalVariables {
  constexpr const auto T0 = temperature(273);
  const auto T_ = T + theta * dT;
  KRS_T = KRS * exp(Ea_R * (1.0/(T0 + T_) - 1.0/(T0 + Tref)));
  KRD_T = KRD * exp(Ea_R * (1.0/(T0 + T_) - 1.0/(T0 + Tref)));
  NRS_T = NRS * exp(Ea_R * (1.0/(T0 + T_) - 1.0/(T0 + Tref)));
  NRD_T = NRD * exp(Ea_R * (1.0/(T0 + T_) - 1.0/(T0 + Tref)));
  NIS_T = NIS * exp(Ea_R * (1.0/(T0 + T_) - 1.0/(T0 + Tref)));
  NID_T = NID * exp(Ea_R * (1.0/(T0 + T_) - 1.0/(T0 + Tref)));
  lambda = computeLambda(young,nu);
  mu     = computeMu(young,nu);
}
```

```
@Integrator {
  h_el = ELTSIZE1/coef1;
  Bt =  (h_el *ft )/ (gf-(0.5*e0*h_el*ft));
  constexpr const auto id = Stensor::Id();
//  _   _
//| | | |
//| |_| |__   ___    ___ _ __ ___  ___ _ __
//| __| '_ \ / _ \  / __| '__/ _ \/ _ \ '_ \
//| |_| | | |  __/ | (__| | |  __/  __/ |_) |
// \__|_| |_|\___|  \___|_|  \___|\___| .__/
//                                    | |
//                                    |_|

//sig/(1-d): Effective stress applied to undamaged part of the concrete

  const auto stresP = trace(sig/(1-d)) / 3.0;
  Stensor stresD = (sig/(1-d)) - stresP *id;

  fESPHR = dESPHR-(((stresP)-KRS_T*(ESPHR+dESPHR))/NRS_T)*dt;
  fEDEVR = dEDEVR-(((stresD)-KRD_T*(EDEVR+dEDEVR))/NRD_T)*dt;

  fESPHI = dESPHI-((stresP)/(NIS_T*pow(t0+0.5*dt,Alpha)))*dt;
  fEDEVI = dEDEVI-((stresD)/(NID_T*pow(t0+0.5*dt,Alpha)))*dt;

  fEF    = dEF - (dEDEVR+dEDEVI + (dESPHR+dESPHI)*id);
```

```
//  _   _                _
//| | | |              | |
//| |_| |__   ___    __| | __ _ _ __ ___   __ _  __ _  ___
//| __| '_ \ / _ \  / _` |/ _` | '_ ` _ \ / _` |/ _` |/ _ \
//| |_| | | |  __/ | (_| | (_| | | | | | | (_| | (_| |  __/
// \__|_| |_|\___|  \__,_|\__,_|_| |_| |_|\__,_|\__, |\___|
//                                               __/ |
//                                              |___/

  // Computation of creep strain
  const auto e_cr = eval(EF+theta*dEF);

  //Computation of elastique strain
  const auto e_elas    = eval(eel+theta*deel);

  //computation of eigenvalues of elastic and creep strain tensors
  const auto e_vp = e_elas.computeEigenValues();
  const auto e_creep = e_cr.computeEigenValues();

  auto square_ppos = [](const strain& v) { return v > 0 ? v * v : 0; };

  // equivalent strain

  e_eq = sqrt(
        square_ppos(e_vp[0]) + square_ppos(e_vp[1]) + square_ppos(e_vp[2])+

        Beta * (square_ppos(e_creep[0]) + square_ppos(e_creep[1]) + square_ppos(e_creep[2]))

        );

  // Computation of damage d

  if (e_eq > e0) {

    d = max(d, 1 - (e0 / e_eq) * exp(Bt * (e0 - e_eq)));

  }
  const auto s = lambda * trace(e_elas) * id + 2 * mu * (e_elas);

  // Decomposition of the stress tensor in positive and negative
  const auto sp = positive_part(s);
  const auto sn = s - sp;

  // Computation of total stress
  sig = (1 - d) * sp + (1 - pow(d, a)) * sn;

  feel   = deel-(deto - dEF);
}
```

```
@ComputeFinalStress {

  auto square_ppos = [](const strain& v) { return v > 0 ? v * v : 0; };
  constexpr const auto id = Stensor::Id();
  const auto e_elas_f = eel.computeEigenValues();
  const auto e_creep_f = EF.computeEigenValues();

  e_eq = sqrt(
          square_ppos(e_elas_f[0]) + square_ppos(e_elas_f[1]) + square_ppos(e_elas_f[2])+
          Beta * (square_ppos(e_creep_f[0]) + square_ppos(e_creep_f[1]) + square_ppos(e_creep_f[2]))
          );//---> Official Theory

  if (e_eq > e0) {
    d = max(d, 1 - (e0 / e_eq) * exp(Bt * (e0 - e_eq)));
  }
  const auto sigma0 = lambda * trace(eel) * id + 2 * mu * (eel);
  const auto sigma0_p = positive_part(sigma0);
  const auto sigma0_n = sigma0 - sigma0_p;
  // contrainte total
  sig = (1 - d) * sigma0_p + (1 - pow(d, a)) * sigma0_n;
}
```


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5 . Validation Study

Validation test-case : Uniaxial Study

Magazine of Concrete Research, 2005, 57, No. 10, December, 623–634

Experimental studies on creep of sealed concrete under multiaxial stresses

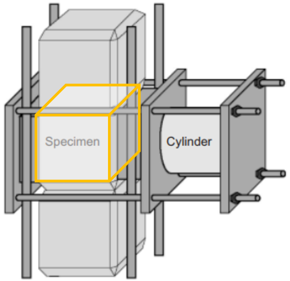
J. K. Kim,* S. H. Kwon,* S. Y. Kim,† Y. Y. Kim*

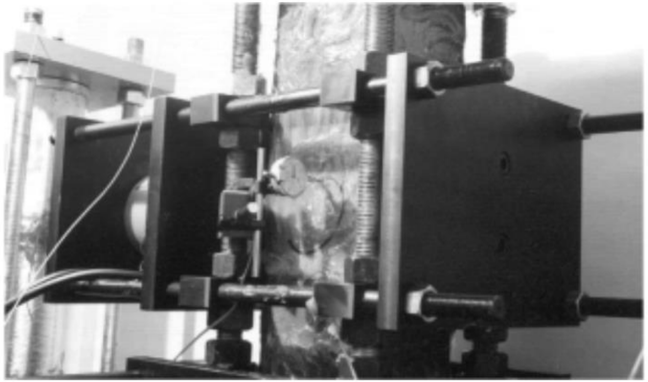
Korea Advanced Institute of Science and Technology; Chonnam National University

The majority of research studies and prediction models on the creep of concrete have been concerned with the uniaxial stress state. Research on creep under multiaxial stresses, however, has been relatively scarce even though concrete is subjected to multiaxial stresses in many structural members and structures. Although some experiments on the multiaxial creep of concrete have been performed, the results of these experiments, which mainly considered low-strength concrete, are controversial. Consequently, for today's standards and practice—and for a better understanding of the properties of concrete—more experimental data are needed on the multiaxial creep of concrete with various strengths. In this study, multiaxial creep tests with 27 cubic specimens (200 mm × 200 mm × 200 mm) were carried out for three different strengths of concrete, namely 26, 44 and 54 MPa, and creep strains were measured in three principal directions. From the measured strains, Poisson's ratio at initial loading was obtained, as was Poisson's ratio resulting from creep strain and Poisson's ratio resulting from the combined creep strain and elastic strain. These Poisson's ratios were approximately equal for each concrete mix. The Poisson's ratio at initial loading and the Poisson's ratio for the combined strain increased slightly as the strength of the concrete increased. The volumetric creep strain and deviatoric creep strain were linearly proportional to volumetric stress and deviatoric stress, respectively.

Notation

Introduction





Objective of this study:

⇒ **Validation of the coupled law Burger-FLB by comparison with experimental data from Chonnam National University [3]**

[3]Experimental studies on creep of sealed concrete under multiaxial stresses
J. K. Kim,* S. H. Kwon,* S. Y. Kim,† Y. Y. Kim*
Korea Advanced Institute of Science and Technology; Chonnam National University

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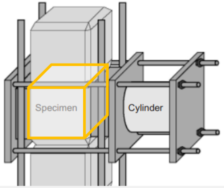
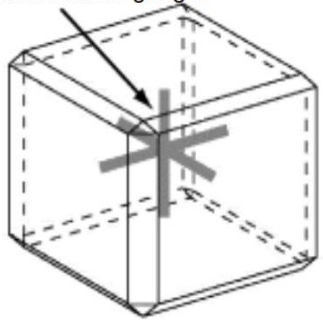
5 . V&V Study

Validation test-case : KIM Study

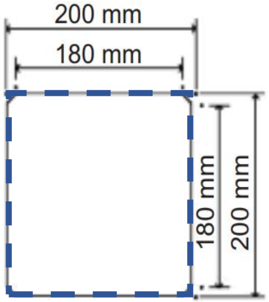
Details of Kim[3] experimental test (Creep Only)

[3]Experimental studies on creep of sealed concrete under multiaxial stresses
J. K. Kim,* S. H. Kwon,* S. Y. Kim,† Y. Y. Kim*
Korea Advanced Institute of Science and Technology; Chonnam National University

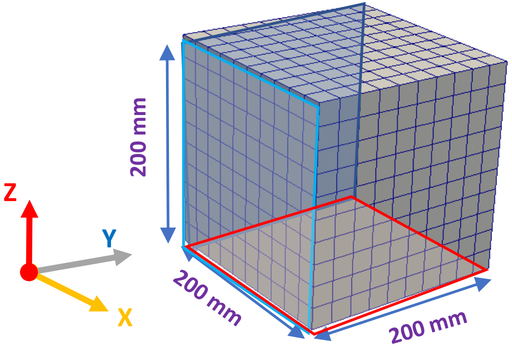




Gauge installation

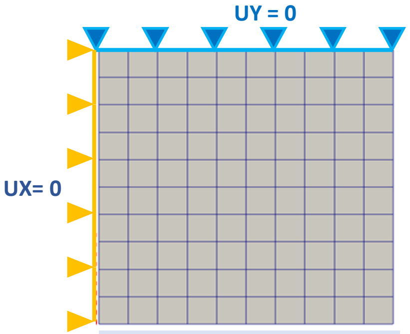


Cross-section of test specimen

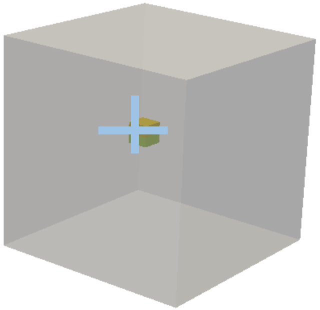


3D FEM

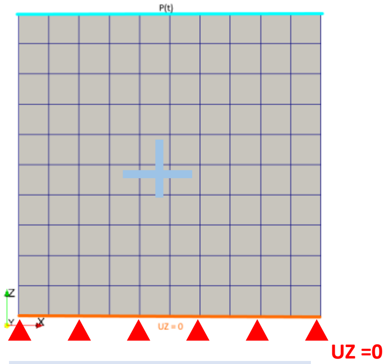
Boundary Conditions



Top view



Gauge of FEM
(for FE Results)



Lateral view

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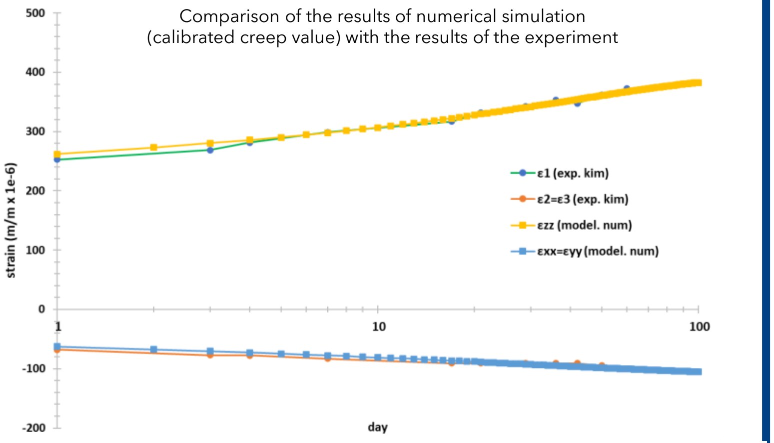
5 . V&V Study

Validation test-case : KIM Study – Uniaxial

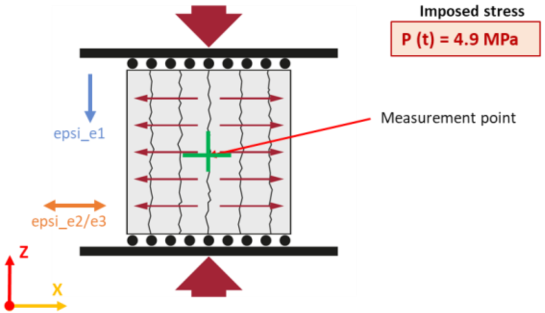


Material

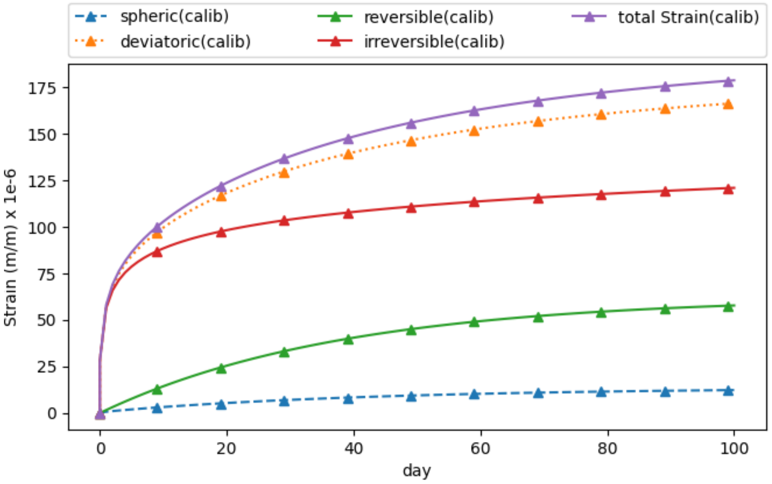
- Burger parameters have been calibrated to achieve the strain from the Kim experiment (keeping in mind that Creep Poisson's ratio is keeping constant)

Calibrated creep parameters

NRD	**=**	**2.07E+17**
NID	**=**	**2.33E+11**
KRD	**=**	**5.26E+10**
KRS	**=**	**1.28E+11**
NRS	**=**	**4.80E+17**
NIS	**=**	**1.57E+13**



lateral view of 3D model



Analysis

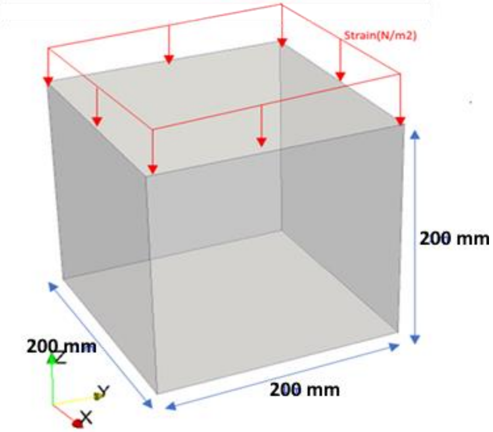
- The values obtained with the simulation are in good agreement with the values of the results of the Kim
- the reconstruction of reversible and irreversible strains is physically correct

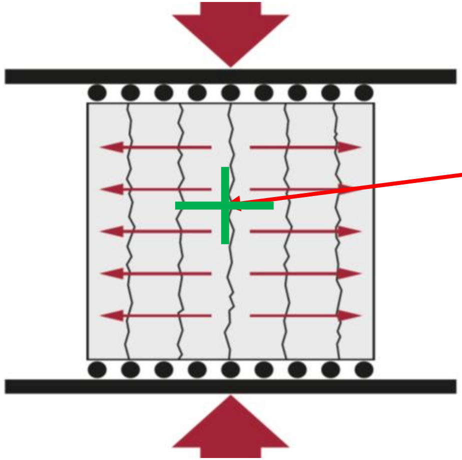
5 . V&V Study

Enable damage to KIM Study (verification) + Beta influence

Loading

The applied pressure is increased by a factor of 2.5 compared to the initial model (and experiment) to enable the damage brought by creep itself





Imposed stress

P (t) = 4.9 MPa x 2.5

Measurement point

As the damage is homogeneous, no visual is being proposed

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5 . V&V Study

Enable damage to KIM Study (verification) + Beta influence

Full Name	Name	Value	Type	Model
Young Modulus	E	24010 MPa	Material	ELAS/FLB
Fracture Energy	Gf	60 J/mm^2	Material	FLB
Tensile Strength	f_t	4 MPa	Material	FLB
--	α	60	Material	FLB
Poisson's ratio	v	0.168	Material	ELAS
viscosity associated with deviatoric	NRD	2.07E+17 Pa	Material	BURGER
viscosity connects associated with the deviatoric unrecoverable deformations	NID	2.33E+11 Pa.s	Material	BURGER
rigidity connects associated with deviatoric	KRD	5.26E+10 Pa	Material	BURGER
rigidity connects associated with spherical	KRS	1.28E+11 Pa	Material	BURGER
viscosity connects associated with spherical	NRS	4.80E+17 Pa.s	Material	BURGER
viscosity connects associated with the spherical unrecoverable deformations	NIS	1.57E+13 Pa.s	Material	BURGER
creep part of the damage Beta	Beta	0 – 1 (variation → 0 ; 0.2; 0.4; 0.6; 0.8;1)	Coupling	FLB-BURGER

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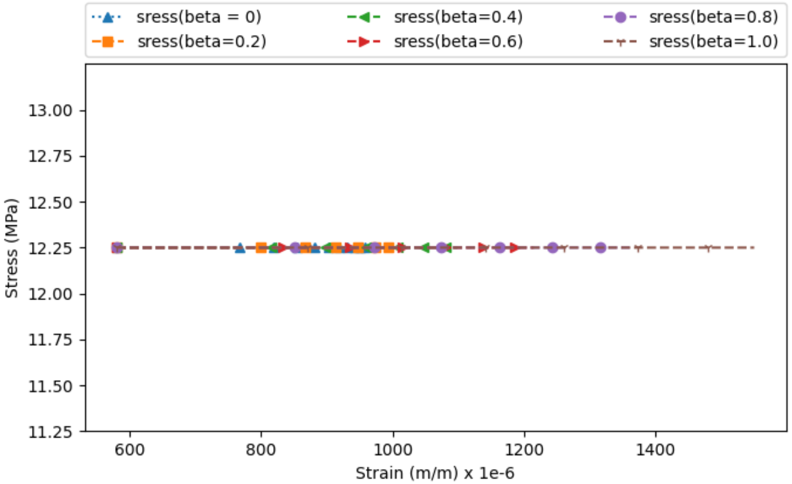
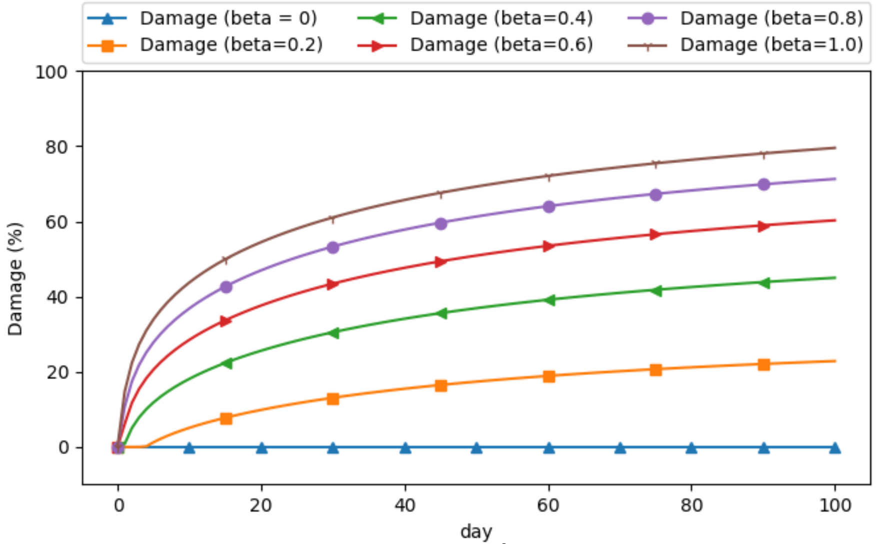
5 . V&V Study

Enable damage to KIM Study (verification) + Beta influence



Applied Stress (total strain evolution)



Damage Evolution

→ More beta is close to one, more the damage linked the basic creep is taking into account

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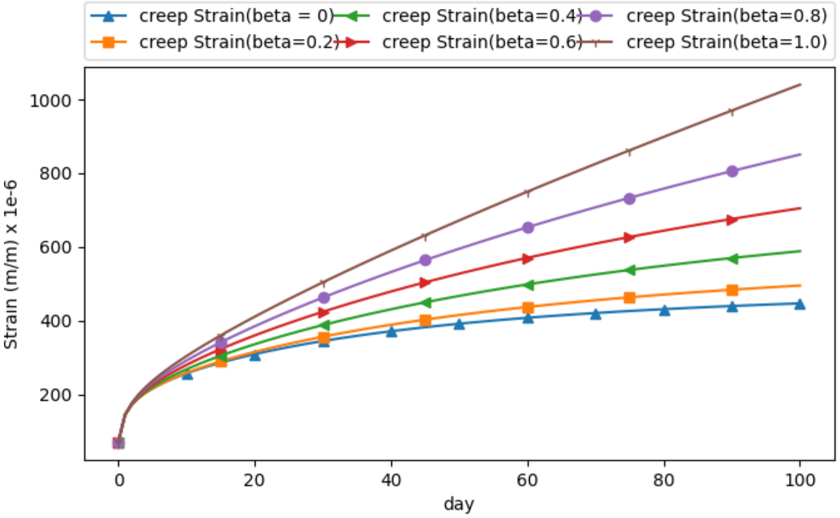
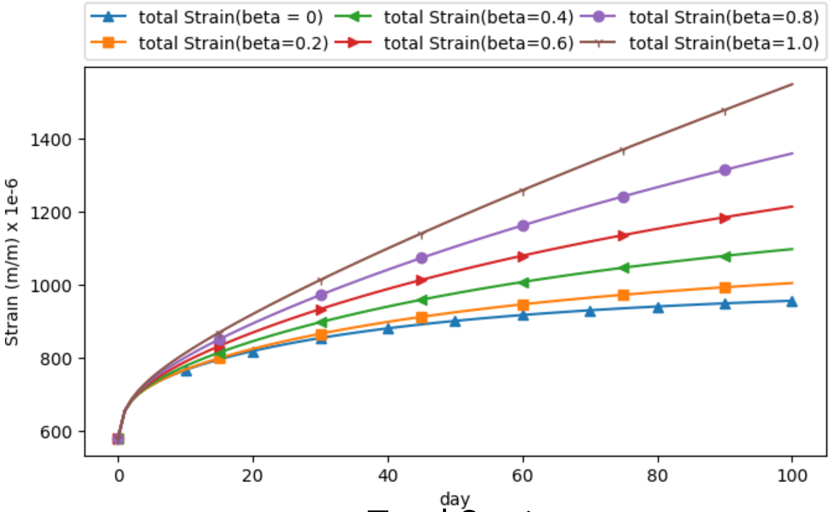
5 . V&V Study

Enable damage to KIM Study (verification) + Beta influence



Creep Strains

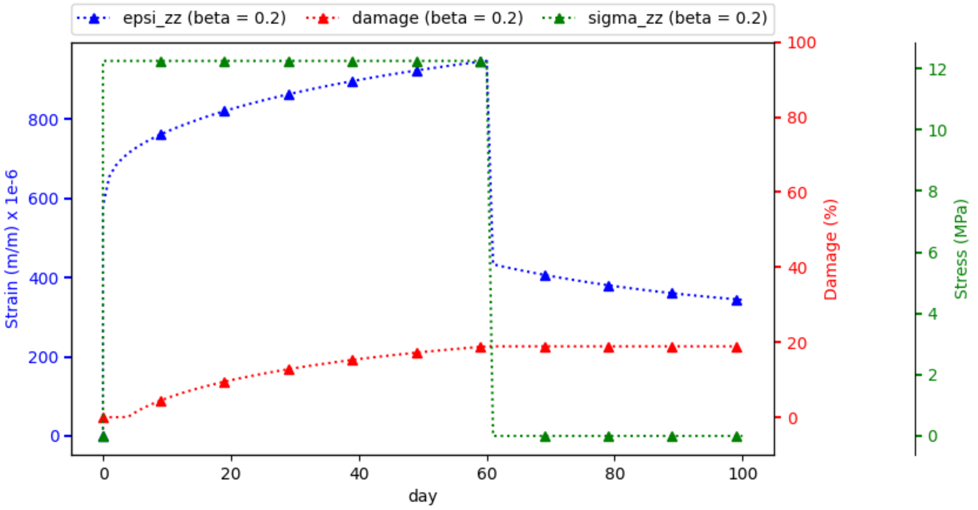


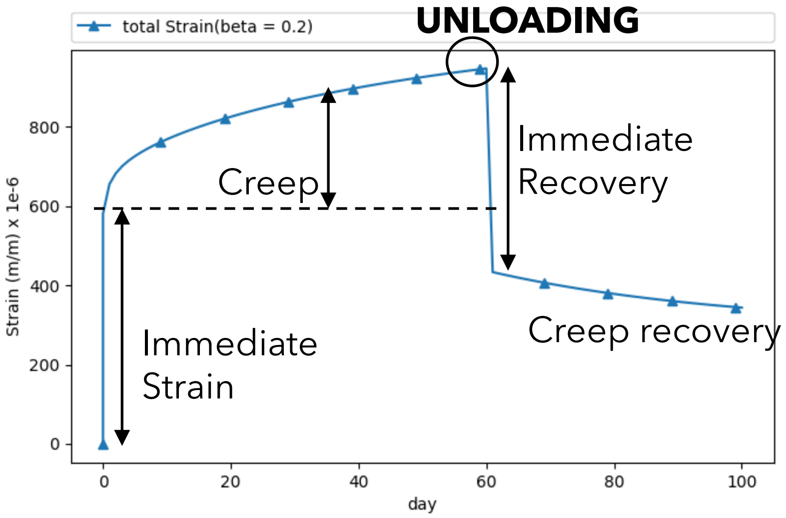
Total Strains

→ **More beta is close to one, more the damage is and more the strain is**

5 . V&V Study

Enable damage to KIM Study (verification) : Beta set to 0.2 + Unloading





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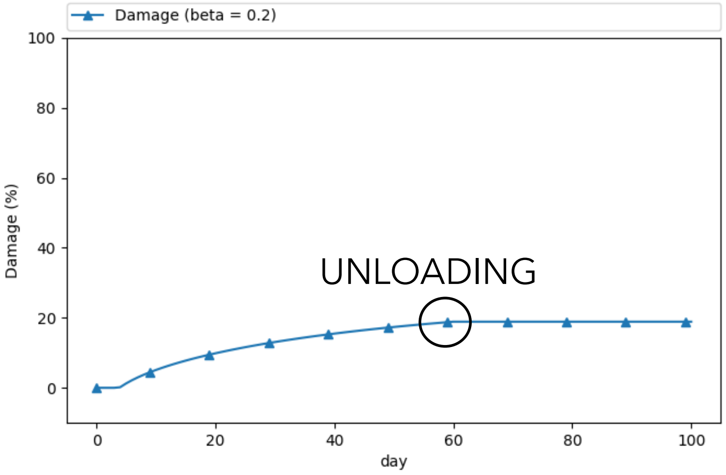
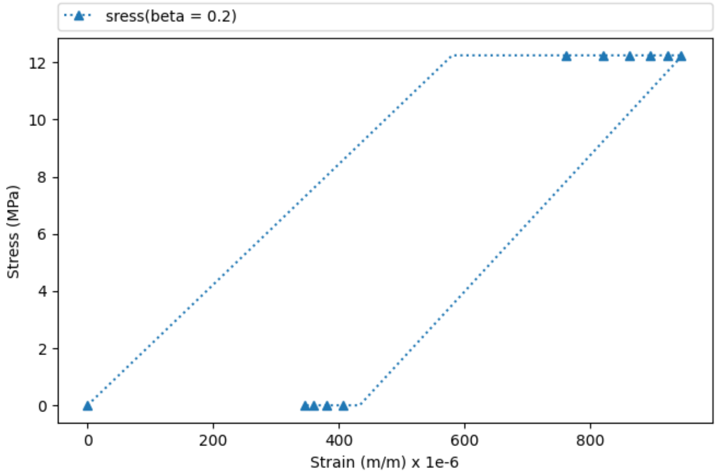
5 . V&V Study

Enable damage to KIM Study (verification) : Beta set to 0.2 + Unloading



Damage Evolution



Macroscopic Response

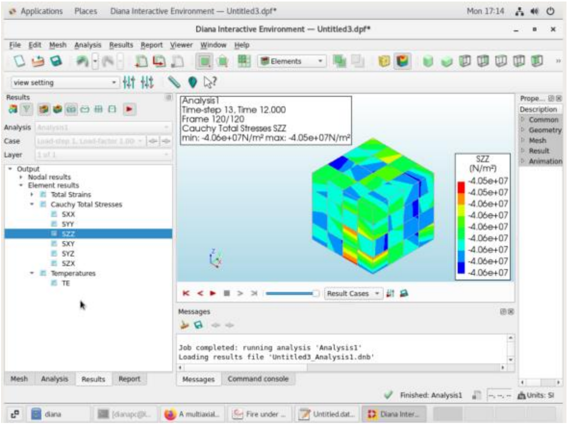
6 . Conclusion and Perspective

Conclusion

- A coupled model has been developed : Damage + Basic creep (tested under code_aster)
- This models contains few parameters (experimentally accessible with calibration)
- Burger parameters influences have been analysed *(not showed in that presentation)*
- The coupling with Thermal creep has not been fully validated yet (the mfront is ready)
- Primary results are encouraging : Burger_FLB gives a good accordance to the basic creep theory

Perspective

- Extend to an industrial test-case (HPB Pre-stressed Vessel)
- CEA developed Mfront/Diana FEA interface to support UK supply chain
- Tested by EDF Energy UK Engineer through Diana Mfront Interface



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Questions time !

THANKS FOR YOUR ATTENTION