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ArGEnCo

SAFIR MANUAL

Materials SILCON_ETC and CALCON_ETC

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I. INTRODUCTION

This document describes the material models SILCON_ETC and CALCON_ETC, developed at University of Liege and implemented in the software SAFIR. The material models SILCON_ETC and CALCON_ETC are based on the Explicit Transient Creep (ETC) constitutive model for concrete at elevated temperature, developed by the authors of this document.

The SAFIR materials SILCON_ETC and CALCON_ETC are based on the Explicit Transient Creep Eurocode constitutive model (ETC) for siliceous and calcareous concrete at elevated temperature.

The ETC model is a uniaxial material model for concrete.
The ETC model is based on the concrete model of Eurocode EN1992-1-2 (EC2), except that in the ETC model the transient creep strain is treated by an explicit term in the strain decomposition whereas in the EC2 model the effects of transient creep strain are incorporated implicitly in the mechanical strain term. The variation of compressive strength and tensile strength with temperature, as well as the thermal properties, are taken from EN1992-1-2.

The references for the ETC concrete model are the following:

T. Gernay, "Effect of Transient Creep Strain Model on the Behavior of Concrete Columns Subjected to Heating and Cooling", *Fire Technology*, accepted for publication, http://www.springerlink.com/content/3362rp1hv5355462/fulltext.pdf

T. Gernay, J-M Franssen, "A Comparison Between Explicit and Implicit Modelling of Transient Creep Strain in Concrete Uniaxial Constitutive Relationships", *Proceedings of the Fire and Materials 2011 Conference*, San Francisco, pp. 405-416, 2011.
http://hdl.handle.net/2268/76564

T. Gernay, J-M Franssen, "Consideration of Transient Creep in the Eurocode Constitutive Model for Concrete in the Fire situation", *Proceedings of the Sixth International Conference Structures in Fire*, Michigan State University, pp. 784-791, 2010.
http://hdl.handle.net/2268/18295

I.1. Nomenclature

T	Temperature
T_{max}	Maximum temperature in the history of the point
ν	Poisson ratio
α	Parameter for thermal conductivity
k	Thermal conductivity
σ	Stress (uniaxial)
ε_{tot}	Total strain (uniaxial)
ε_{res}	Residual strain
ε_{th}	Thermal strain
ε_{tr}	Transient creep strain
ε_{σ}	Instantaneous stress-dependent strain
ε_{p}	Plastic strain
ε_{el}	Elastic strain
$\varepsilon_{c1,\mathrm{EC2}}$	Peak stress strain of Eurocode 2
$\varepsilon_{c1,\mathrm{ENV}}$	Peak stress strain of ENV (minimum value)
$\varepsilon_{c1,\mathrm{ETC}}$	Peak stress strain of ETC model
$\varepsilon_{c0,\mathrm{EC2}}$	Strain to 0 stress of Eurocode 2
$\varepsilon_{c0,\mathrm{ETC}}$	Strain to 0 stress of ETC model
f_{ck}	Compressive strength at 20°C
$f_{c,T}$	Compressive strength (temperature-dependent)
f_{tk}	Tensile strength at 20°C
$f_{t,T}$	Tensile strength (temperature-dependent)
E_t	Tangent modulus
$\phi(T)$	Transient creep function
$E_{0,\mathrm{ETC}}$	Elastic modulus of the ETC model

I.2. User input

I.2.1. *User input for thermal analysis*

If CMAT(NM) = SILCON_ETC , CALCON_ETC - 6 parameters are required (1 line only)

PARACOLD(3,NM)	Specific mass	[kg/m^3]
PARACOLD(5,NM)	Moisture content	[kg/m^3]
PARACOLD(6,NM)	Convection coefficient on hot surfaces	[W/m^{2}K]
PARACOLD(7,NM)	Convection coefficient on cold surfaces	[W/m^{2}K]
PARACOLD(8,NM)	Relative emissivity	[-]
PARACOLD(4,NM)	Parameter for thermal conductivity, α	[-]

Note: according to clause 3.3.3 of EN-1992-1-2, the thermal conductivity can be chosen between lower and upper limit values. The parameter α allows any intermediate value to be taken according to $k(T) = k_{lower}(T) + \alpha\left(k_{upper}(T) - k_{lower}(T)\right)$ with $\alpha \in [0,1]$.

I.2.2. *User input for mechanical analysis*

If CMAT(NM) = SILCON_ETC , CALCON_ETC - 3 parameters are required (1 line only)

PARACOLD(2,NM)	Poisson ratio ν	[-]
PARACOLD(3,NM)	Compressive strength f_{ck}	[N/m^2]
PARACOLD(4,NM)	Tensile strength f_{tk}	[N/m^2]

I.3. Input of the material subroutines

The input parameters are:

- The current temperature at the integration point T
- The maximum temperature at the integration point T_{max}
- The total strain at the current iteration $\varepsilon_{tot}^{(i)}$
- Possibly, the residual strain at the current iteration $\varepsilon_{res}^{(i)}$
- The evolution laws of the material properties with temperature:
    - Compressive strength $f_{c,T}$
    - Tensile strength $f_{t,T}$
    - Strain to 0 stress according to EC2 $\varepsilon_{c0,\mathrm{EC2}}$
    - Strain to peak stress according to EC2 $\varepsilon_{c1,EC2}$
    - Strain to peak stress according to ENV (min value) $\varepsilon_{c1,ENV}$
    - Thermal strain ε_{th}

Moreover, the routine keeps the values of some parameters from one step to another because they will be used:

- The plastic strain at the previous (converged) time step $\varepsilon_{p}^{(s-1)}$
- The transient creep strain at the previous (converged) time step $\varepsilon_{tr}^{(s-1)}$
- The stress at the previous (converged) time step $\sigma^{(s-1)}$

I.4. Output of the material subroutines

The output parameters are:

- The thermal strain $\varepsilon_{th}^{(s)}$
- The transient creep strain $\varepsilon_{tr}^{(s)}$
- The plastic strain $\varepsilon_{p}^{(s)}$
- The stress $\sigma^{(s)}$
- The tangent modulus $E_{t}^{(s)}$

II. DESCRIPTION OF THE MATERIAL LAW

II.1. Thermal properties

The thermal models for the materials SILCON_ETC (siliceous concrete) and CALCON_ETC (carbonate concrete) are taken from EN1992-1-2. The routine implemented in SAFIR for the thermal analysis with material SILCON_ETC is exactly the same as the routine with material SILCONCEC2, and CALCON_ETC is the same as CALCONCEC2.

II.2. Mechanical properties

II.2.1. General procedure

The general procedure of the finite elements calculation method implemented in the non linear software SAFIR is schematized in Figure 1. The following notation has been used: $\underline{f}_{\text{ext}}$ is the vector of the external nodal forces at a particular moment, $\Delta\underline{f}$ is a given increment of force between step (*s*-1) and step (*s*), *T* is the temperature (which has been calculated for every time step before the beginning of the mechanical calculation), $\underline{r}^{(i)}$ is the residual force after (*i*) rounds of iteration, $\underline{f}_{\text{int}}$ is the vector of the internal forces, $\Delta\underline{u}$ is the increment of displacement corresponding to $\Delta\underline{f}$, $\underline{\underline{K}}^{(i)}$ is the stiffness matrix, $\underline{\underline{B}}$ is the matrix linking deformations and nodal displacements and $\underline{\underline{D}}_t$ is the tangent stiffness matrix of the non linear material law. In the particular case of the ETC concrete model that is explained here, as it is a uniaxial material model, some notation could be simplified in scalar notation.

The thermal strain is calculated at the beginning of each time step, as a function of the temperature. This thermal strain does not vary during a time step.

The transient creep strain is also calculated at the beginning of each time step. As the stress at the equilibrium at the end of step (*s*) is not known yet when the transient creep strain is calculated, it was decided to calculate the transient creep strain as a function of the stress at the previous (converged) time step. The transient creep strain calculation takes into account the stress-temperature history. Between step (*s*) and step (*s*-1), there is an increment in transient creep strain if and only if the three following conditions are fulfilled:

i. The temperature has increased between step (*s*) and step (*s*-1)
ii. The (converged) stress at time step (*s*-1) is a compressive stress
iii. The tangent modulus of the material is positive, i.e., the material is in the ascending branch of the stress-strain relationship

In this case, the increment in transient creep strain is calculated as:

$$\Delta\varepsilon_{tr} = \left[\phi\left(T^{(s)}\right) - \phi\left(T^{(s-1)}\right)\right] \frac{\sigma^{(s-1)}}{f_{ck}}$$

where $\sigma^{(s-1)}$ is the compressive stress at the previous time step, f_{ck} is the compressive strength at 20°C and $\phi(T)$ is a temperature-dependent function. The function $\phi(T)$ is calculated as:

$$\phi(T)=\frac{2}{3}\,\frac{\left(\varepsilon_{c1,EC2}-\varepsilon_{c1,ENV}\right)}{\left(f_c/f_{ck}\right)}$$

If the temperature has decreased or remained constant between step (s) and step (s-1), there is no increment in transient creep strain. Similarly, if the material is subjected to tension or if the material exhibits its softening behavior after the peak stress in compression, it has been assumed that there is no increment in transient creep strain. As the function $\phi(T)$ is growing with temperature, the transient creep term can only increase. The increment of transient creep strain is the same for loading and unloading as long as the stress is in compression.

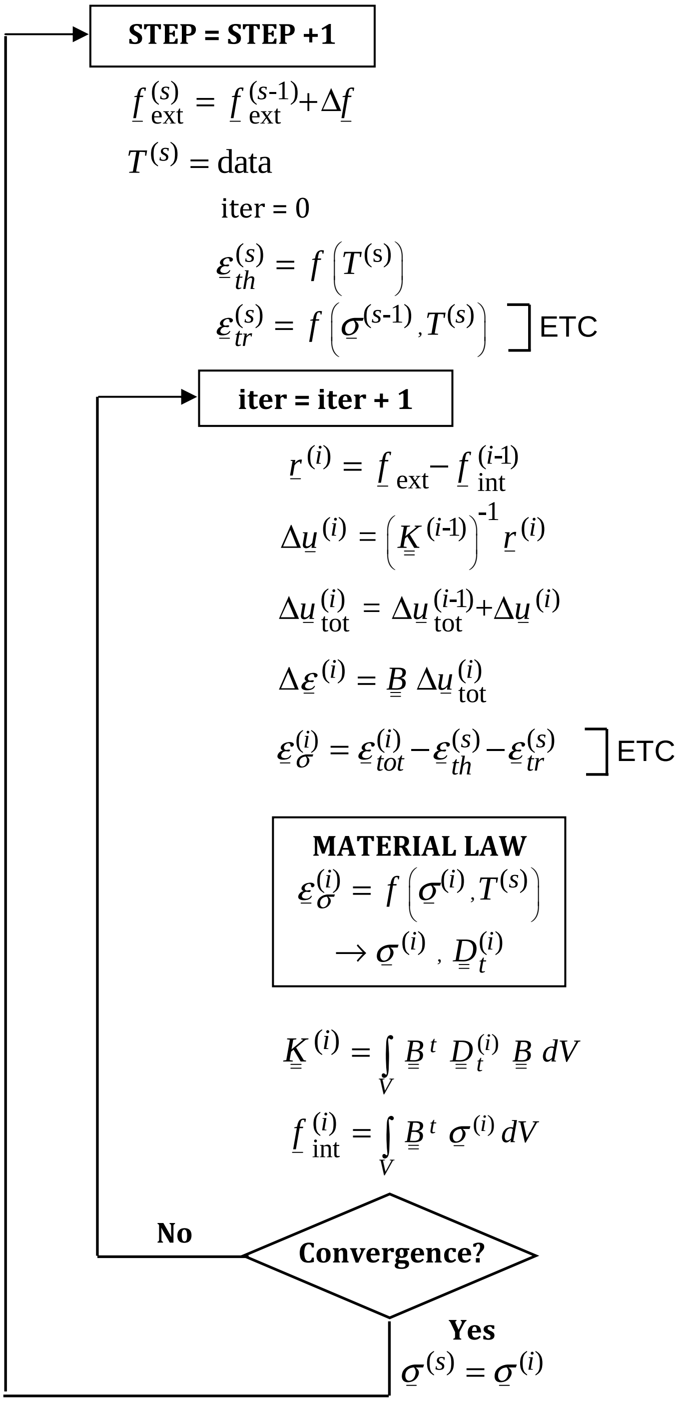

Figure 1 : Flow chart of the implementation of the ETC concrete model in SAFIR

After calculation of the thermal strain and the transient creep strain, it is possible to calculate the instantaneous stress-dependent strain by the following equation:

$$\varepsilon_{\sigma} = \varepsilon_{tot} - \varepsilon_{th} - \varepsilon_{tr} \left(-\varepsilon_{res}\right)$$

This equation is the same as Eq. 4.15 of EN1992-1-2 except that the basic creep strain has not been taken into account in the ETC concrete model.

II.2.2. Concrete in compression

The ETC relationship is written in terms of the instantaneous stress-dependent strain. The ETC stress-strain relationship is made of a nonlinear ascending branch and a descending branch made of two curves, each of them being a third order function of the strain.

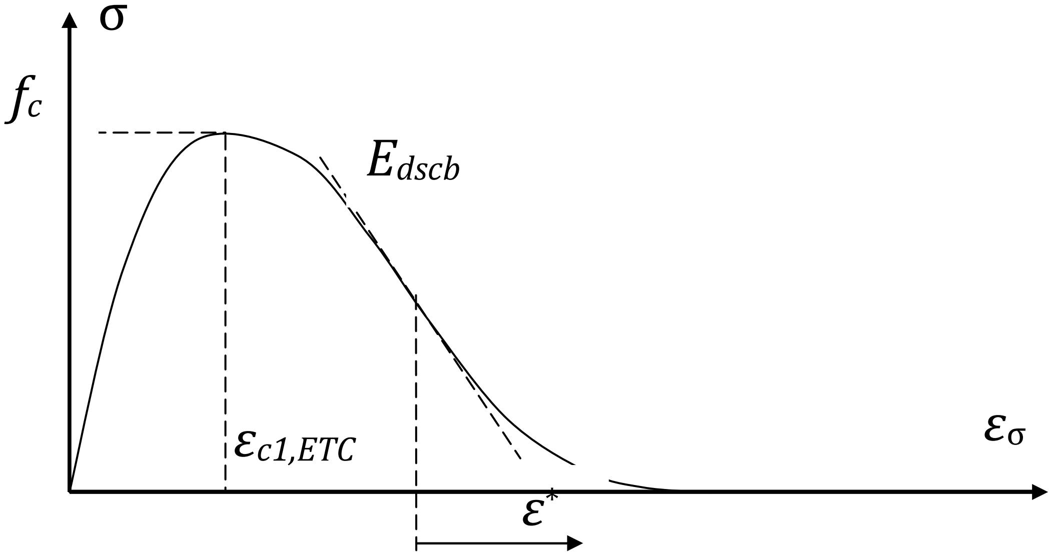

Figure 2 : ETC stress-strain relationship in compression

The ascending branch is characterized by the compressive strength f_c, and the strain at compressive strength $\varepsilon_{c1,\mathrm{ETC}}$ for the ETC relationship. The equation that gives the stress σ and the tangent modulus are, for $\varepsilon_{\sigma} \le \varepsilon_{c1,\mathrm{ETC}}$:

$$\sigma = f_c(T) \frac{2\ \varepsilon_{\sigma}}{\varepsilon_{c1,\mathrm{ETC}}(T)\left(1+\left(\varepsilon_{\sigma}/\varepsilon_{c1,\mathrm{ETC}}(T)\right)^2\right)}$$

$$E_t = 2 f_c \frac{1-\left(\varepsilon_{\sigma}/\varepsilon_{c1,\mathrm{ETC}}\right)^2}{\varepsilon_{c1,\mathrm{ETC}}\left[1+\left(\varepsilon_{\sigma}/\varepsilon_{c1,\mathrm{ETC}}\right)^2\right]^2}$$

The ETC constitutive relationship has a generic form that is similar to the EC2 constitutive relationship, but the EC2 model is written in terms of the mechanical strain.

The strain at compressive strength $\varepsilon_{c1,\mathrm{ETC}}$ is a function of the maximum temperature experienced by the material T_{max}. The relationship between the peak stress strain of the ETC concrete model $\varepsilon_{c1,\mathrm{ETC}}$

(that does not include transient creep strain) and the peak stress strain of the Eurocode 2 concrete model $\varepsilon_{c1,\mathrm{EC2}}$ (that implicitly incorporates transient creep strain) is given by:

$$\varepsilon_{c1,\mathrm{ETC}} = \left(2\,\varepsilon_{c1,ENV} + \varepsilon_{c1,\mathrm{EC2}}\right) / 3$$

The value of the modulus at the origin, i.e. the slope of the curve at the origin, cannot be defined by the user. It comes directly from the equation of the stress-strain relationship:

$$E_{0,\mathrm{ETC}} = 2\ f_c / \varepsilon_{c1,\mathrm{ETC}}\ .$$

The descending branch is made of two 3rd order polynomial from point ($\varepsilon_{c1,\mathrm{ETC}}$; f_c) until point ($\varepsilon_{c0,\mathrm{ETC}}$; *0*). The relationship between the strain at 0 stress of the ETC concrete model $\varepsilon_{c0,\mathrm{ETC}}$ and the strain at 0 stress of the Eurocode 2 concrete model $\varepsilon_{c0,\mathrm{EC2}}$ is given by the following equation:

$$\varepsilon_{c0,\mathrm{ETC}} = \varepsilon_{c0,\mathrm{EC2}} - \left(\varepsilon_{c1,\mathrm{EC2}} - \varepsilon_{c1,\mathrm{ETC}}\right).$$

The slope of the descending branch at the point where the sign of the concavity of the curve changes is noted E_{dscb}. This is the slope at the point of transition from the first to the second third order polynomial. The value of E_{dscb} is given by:

$$E_{dscb} = 2 \frac{f_c}{\varepsilon_{c0,\mathrm{ETC}} - \varepsilon_{c1,\mathrm{ETC}}}$$

The equation that gives the stress σ and the tangent modulus are:

$$\varepsilon^* = \varepsilon_\sigma - \varepsilon_{c1,\mathrm{ETC}} - f_c / E_{dscb}$$

$$\sigma^* = E_{dscb}\ \varepsilon^*$$

If $\varepsilon^* \leq 0$;

$$\sigma = \frac{f_c}{2} - \sigma^* \left(\frac{\sigma^*}{2 f_c} + 1 \right)$$

$$E_t = -E_{dscb} \left(\frac{\sigma^*}{f_c} + 1 \right)$$

If $0 < \varepsilon^* \leq f_c / E_{dscb}$;

$$\sigma = \frac{f_c}{2} + \sigma^* \left(\frac{\sigma^*}{2 f_c} - 1 \right)$$

$$E_t = E_{dscb} \left(\frac{\sigma^*}{f_c} - 1 \right)$$

If $f_c / E_{dscb} < \varepsilon^*$;

$$\sigma = 0$$

$$E_t = 0$$

Figure 3 present the (instantaneous) stress-strain curves in compression for the material SILCON_ETC, for temperatures between 20°C and 1000°C.

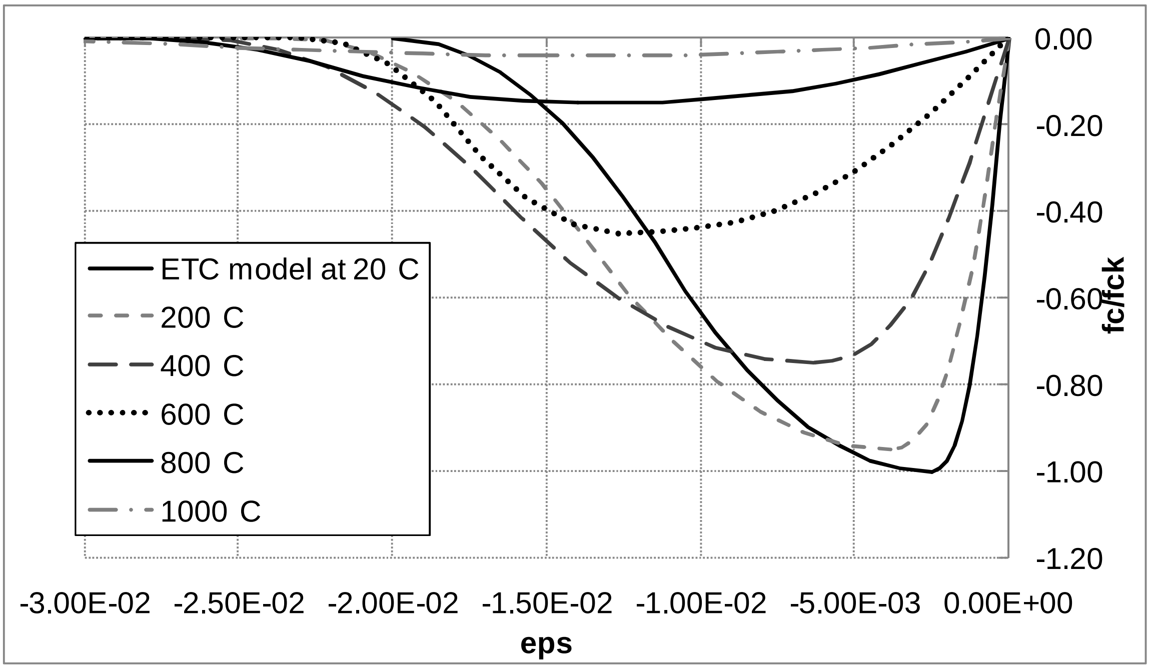

Figure 3: ETC concrete model in compression

If concrete has been loaded in compression and, in a later stage, the strain decreases, the unloading is made according to a plasticity model. This means that the path is a linear decrease from the point of maximum compressive strain in the loading curve parallel to the tangent at the origin.

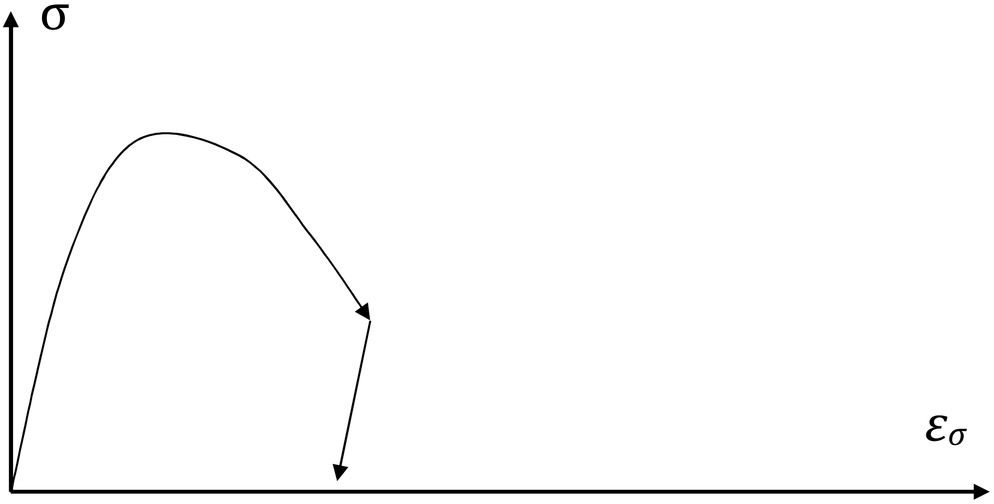

Figure 4 : Unloading in compression – plasticity model

For a material that is first-time heated under compressive stress (i.e. transient test), the ETC concrete model gives the same mechanical strain response as the EC2 concrete model. Indeed in this case, the material develops transient creep strain. In the ETC concrete model, the effects of transient creep strain are added to the instantaneous stress-dependent strain whereas in the EC2 model, the effects of transient creep strain are already incorporated, implicitly in the mechanical strain term (Figure 6). However, the difference between the ETC and the EC2 concrete models is visible when the material is unloaded. In the ETC concrete model, only the elastic strains are recovered whereas in the EC2 model, the transient creep strain is also recovered.

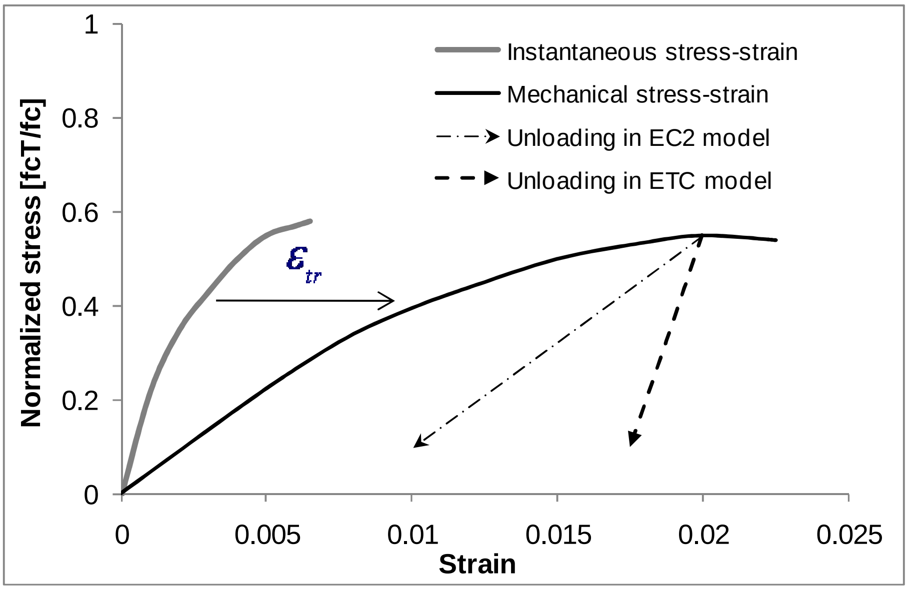

Figure 5 : Concrete behavior at 500°C

For a material that is loaded at (constant) elevated temperature, the mechanical strain response of the ETC and the EC2 models is different. Indeed in this case, no transient creep strain develops in the material so the mechanical strain response of the ETC model is the same as the instantaneous stress-strain response. However, as the effects of transient creep strain are incorporated implicitly in the EC2 model, the response of the EC2 model in case of instantaneous stress-strain test is the same as in case of transient test.

II.2.3. <u>Concrete in tension</u>

The behaviour of concrete in tension is described by a stress-strain relationship. This means that neither the opening of individual cracks nor the spacing between different cracks is present in the model. The cracks are said to be « smeared » along the length of the elements.

The stress-strain relationship is made of a second order ascending branch and a descending branch made of two curves, each of them being a third order function of the strain.

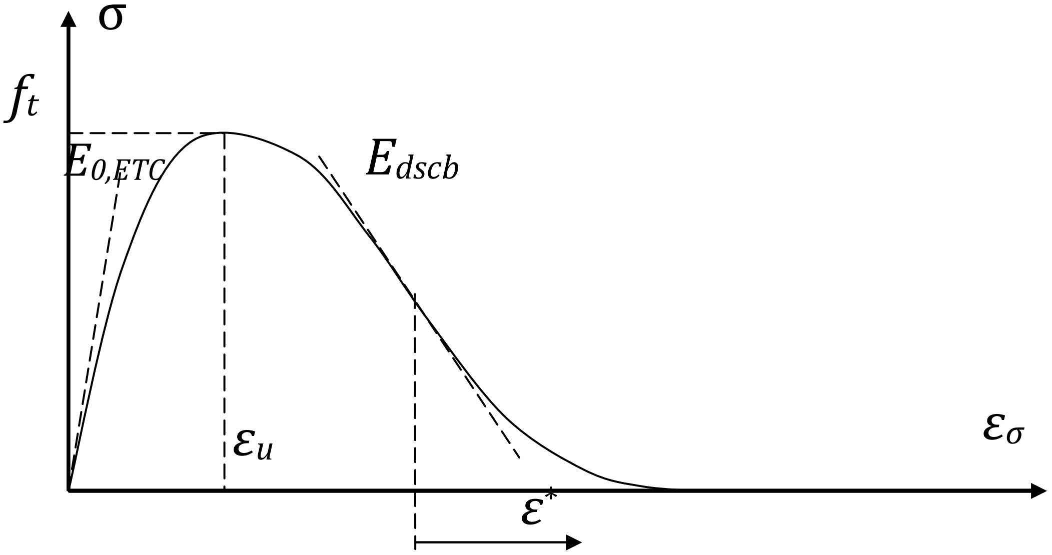

Figure 6 : ETC stress-strain relationship in tension

The ascending branch is characterized by the tensile strength f_t, and the modulus at the origin $E_{0,\mathrm{ETC}}$. The equation that gives the stress σ and the tangent modulus are, for $\varepsilon_\sigma \leq \varepsilon_u$:

$$\varepsilon_u = 2\frac{f_t}{E_{0,\mathrm{ETC}}}$$

$$\sigma = E_{0,\mathrm{ETC}}\ \varepsilon_\sigma \left(1 - \frac{E_{0,\mathrm{ETC}}\ \varepsilon_\sigma}{4\ f_t}\right)$$

$$E_t = E_{0,\mathrm{ETC}} \left(1 - \frac{E_{0,\mathrm{ETC}}\ \varepsilon_\sigma}{2\ f_t}\right)$$

The descending branch is characterized by the point (ε_u ; f_t), by the slope of the descending branch at the point where the sign of the concavity of the curve changes E_{dscb}. The value of E_{dscb} in tension is the same as the value in compression.

The equation that gives the stress σ and the tangent modulus are:

$$\varepsilon^* = \varepsilon_\sigma - \varepsilon_u - f_t / E_{dscb}$$
$$\sigma^* = E_{dscb}\ \varepsilon^*$$

If $\varepsilon^* \leq 0$;

$$\sigma = \frac{f_t}{2} - \sigma^* \left(\frac{\sigma^*}{2 f_t} + 1\right)$$

$$E_t = -E_{dscb} \left(\frac{\sigma^*}{f_t} + 1\right)$$

If $0 < \varepsilon^* \leq f_t / E_{dscb}$;

$$\sigma = \frac{f_t}{2} + \sigma^* \left(\frac{\sigma^*}{2 f_t} - 1\right)$$

$$E_t = E_{dscb} \left(\frac{\sigma^*}{f_t} - 1\right)$$

If $f_t / E_{dscb} < \varepsilon^*$;

$$\sigma = 0$$
$$E_t = 0$$

Figure 7 present the (instantaneous) stress-strain curves in tension for the material SILCON_ETC, for temperatures between 20°C and 500°C.

If concrete has been loaded in tension and, in a later stage, the strain decreases, the unloading is made according to a damage model (Figure 8). This means that the path is a linear decrease from the point of maximum tensile strain in the loading curve to the point of origin in the stress-strain diagram plane.

The modulus at the origin in tension is the same as the modulus at origin in compression for the same temperature.

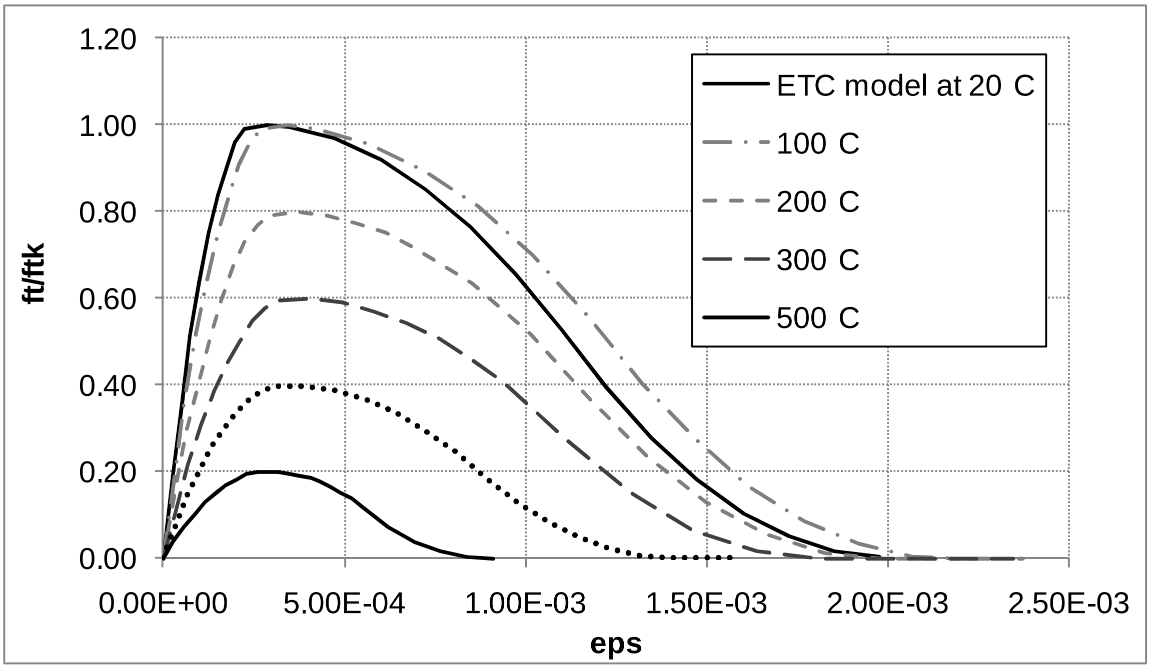

Figure 7 : ETC concrete model in tension

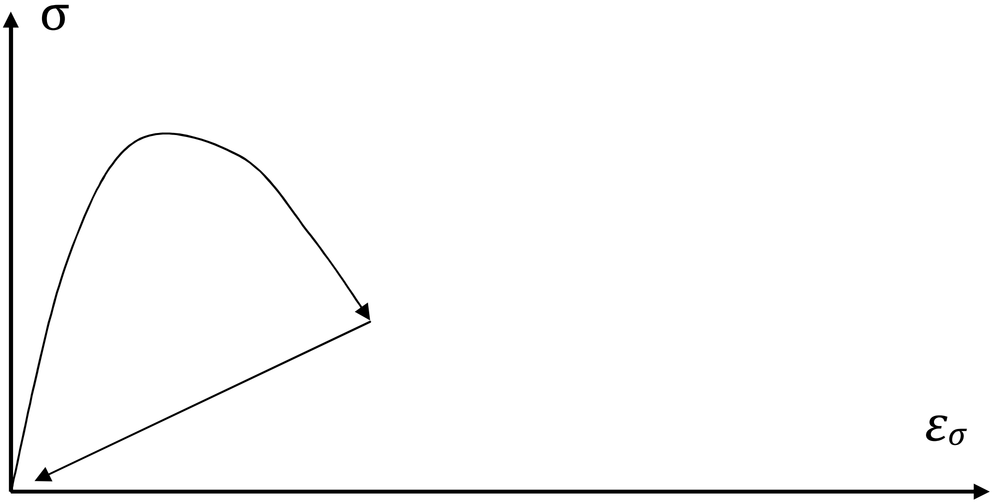

Figure 8 : Unloading in tension – damage model

If the tensile strength at room temperature is modified (and the compressive strength is unchanged), the curves of the stress-strain diagram in tension are scaled accordingly, horizontally as well as vertically. The tangents at the origin remain unchanged. If the compressive strength at room temperature is modified (and the tensile strength is unchanged), the tangent at the origin is modified proportionally and the ductility is modified proportionally to $1/f_c$.

II.2.4. Evolution law of the material properties

During heating, the compressive strength $f_c(T)$ of concrete that is at temperature T is calculated according to :

$$f_c(T) = k_{fc}(T) \,.\, f_{ck}$$

During heating, the tensile strength $f_t(T)$ of concrete that is at temperature T is calculated according to:

$$f_t(T) = k_{ft}(T) \cdot f_{tk}$$

The evolutions of $k_{fc}(T)$ and $k_{ft}(T)$ with temperature are given in Table 1 and Table 2. They are taken from § 3.2.2.1 and § 3.2.2.2 in EN 1992-1-2.

The strain at compressive strength $\varepsilon_{c1,\mathrm{ETC}}$ is a function of the maximum temperature experienced by the material T_{max}. The evolution of $\varepsilon_{c1,\mathrm{ETC}}$ with temperature is also given in Table 1 and Table 2.

Table 1 and Table 2 give also the evolution of the strain at 0 stress of the ETC concrete model $\varepsilon_{c0,\mathrm{ETC}}$, the transient creep phi-function ϕ and the modulus $E_{0,\mathrm{ETC}}$ with temperature.

For siliceous concrete

T [°C]	$f_{c,T}/f_{ck}$	$f_{t,T}/f_{tk}$	epsc1,ETC	eps0,ETC	$E_{0,ETC}/f_{ck}$	Φ
20	1.00	1.00	0.0025	0.0200	800.0	0
100	1.00	1.00	0.0030	0.0215	666.7	0.00100
200	0.95	0.80	0.0038	0.0233	495.7	0.00175
300	0.85	0.60	0.0050	0.0255	340.0	0.00235
400	0.75	0.40	0.0063	0.0263	236.8	0.00489
500	0.60	0.20	0.0087	0.0262	138.5	0.01056
600	0.45	0	0.0127	0.0227	71.1	0.02741
700	0.30		0.0133	0.0258	45.0	0.03889
800	0.15		0.0140	0.0290	21.4	0.07333
900	0.08		0.0150	0.0325	10.7	0.12500
1000	0.04		0.0150	0.0350	5.3	0.25000
1100	0.01		0.0150	0.0375	1.3	1.00000
1200	0		-	-		-

Table 1 : Evolution of the material properties with temperature for ETC siliceous concrete

For calcareous concrete

T [°C]	$f_{c,T}/f_{ck}$	$f_{t,T}/f_{tk}$	epsc1,ETC	eps0,ETC	$E_{0,ETC}/f_{ck}$	Φ
20	1.00	1.00	0.0025	0.0200	800.0	0.00000
100	1.00	1.00	0.0030	0.0215	666.7	0.00100
200	0.97	0.80	0.0038	0.0233	506.1	0.00172
300	0.91	0.60	0.0050	0.0255	364.0	0.00220
400	0.85	0.40	0.0063	0.0263	268.4	0.00431
500	0.74	0.20	0.0087	0.0262	170.8	0.00856
600	0.60	0	0.0127	0.0227	94.7	0.02056
700	0.43		0.0133	0.0258	64.5	0.02713
800	0.27		0.0140	0.0290	38.6	0.04074
900	0.15		0.0150	0.0325	20.0	0.06667
1000	0.06		0.0150	0.0350	8.0	0.16667
1100	0.02		0.0150	0.0375	2.7	0.50000
1200	0		-	-		-

Table 2 : Evolution of the material properties with temperature for ETC calcareous concrete

Figure 9 shows the thermal strain as a function of temperature. A residual thermal expansion or shrinkage has been considered when the concrete is back to ambient temperature. The value of the residual value is a function of the maximum temperature and is given in Table 3, taken from experimental tests made by Schneider in 1979. Negative values indicate residual shortening whereas positive values indicate residual expansion.

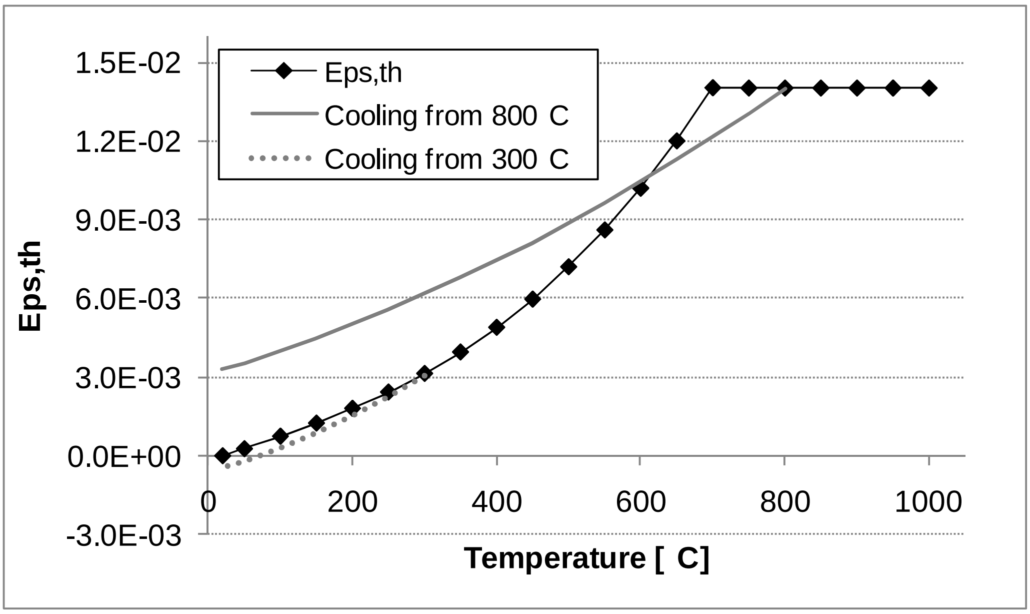

Figure 9 : Thermal strain implemented in the ETC concrete model

T_{max} [°C]	$\varepsilon_{residual}$ (20°C) [10^{-3}]
20	0
300	-0,58
400	-0,29
600	1,71
800	3,29
≥ 900	5,00

Table 3 : Residual thermal expansion of concrete implemented in the ETC concrete model

III. VALIDATION TESTS

The subroutine SILCON_ETC implemented in SAFIR is tested on a “structure” made of one single BEAM finite element. The cross section of the BEAM finite element is made of 4 fibers that have all the same temperature.
All the results presented here have been obtained with the software SAFIR developed at the University of Liege, version 2011.b.0.

III.1. Instantaneous stress-strain curves

The element is first heated and then loaded while the temperature remains constant.

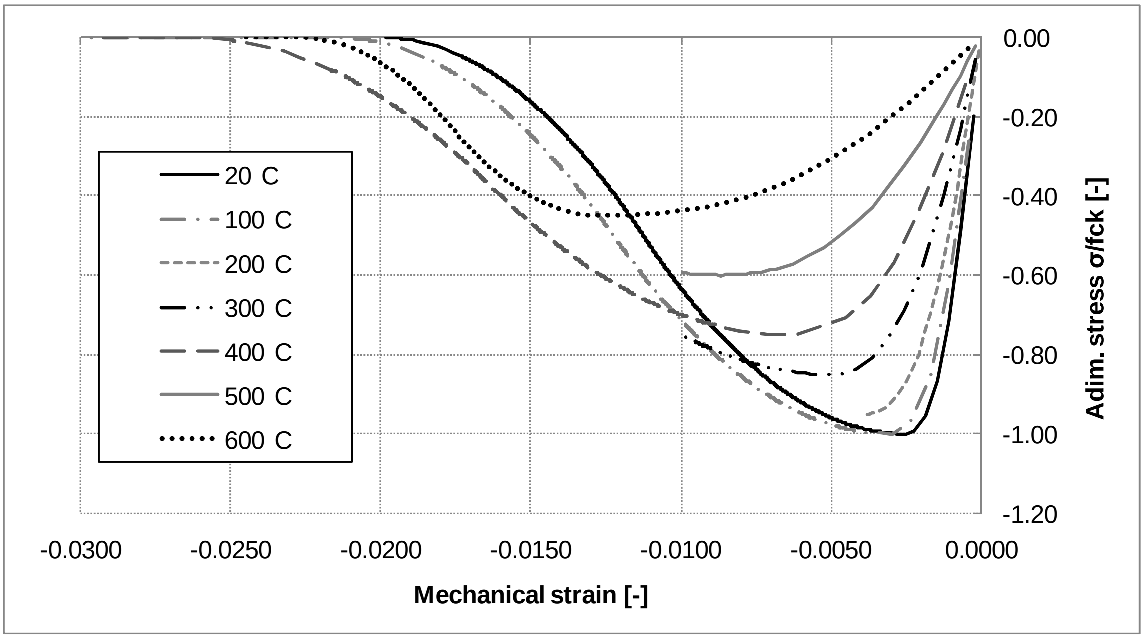

Figure 10 : ETC concrete model in compression

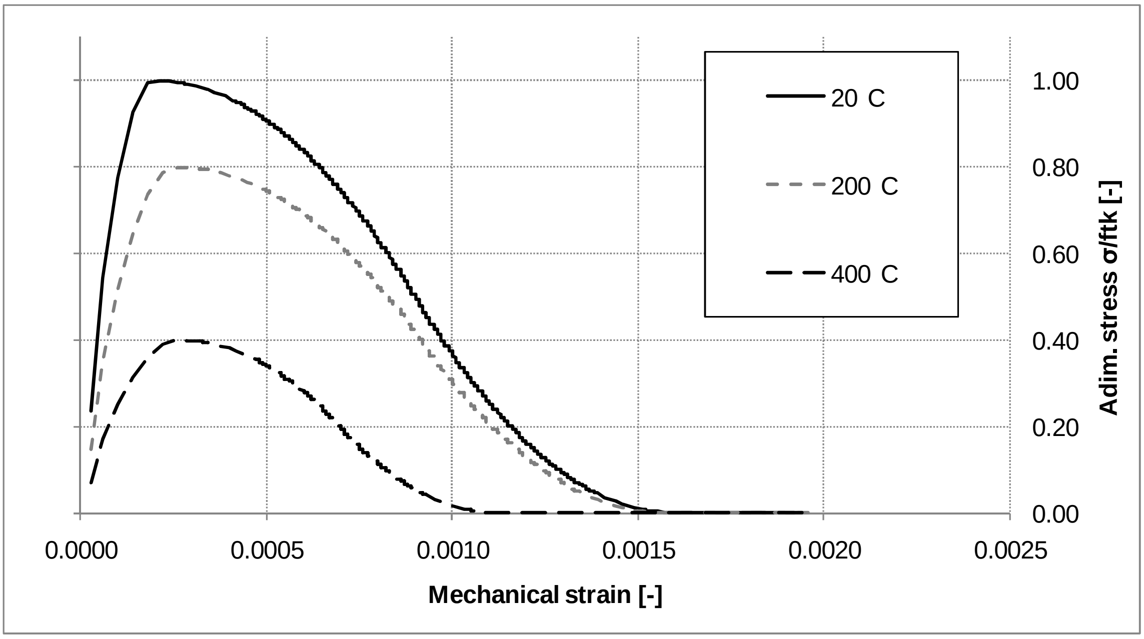

Figure 11 : ETC concrete model in tension

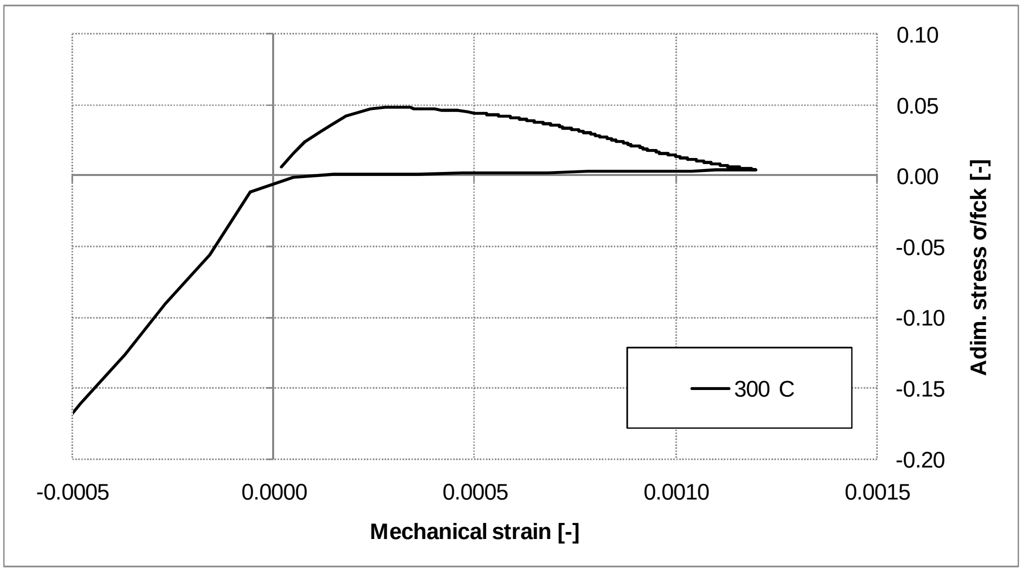

Figure 12 : Transition zone between tension and compression

III.2. Transient test curves

The transient test curve at a given temperature is obtained by the following process: the element is loaded to a certain stress level; then it is heated to the requested temperature; the process is repeated several times for different load levels. Each transient test curve is thus the result of numerous simulations varying by the stress level that is applied before heating.

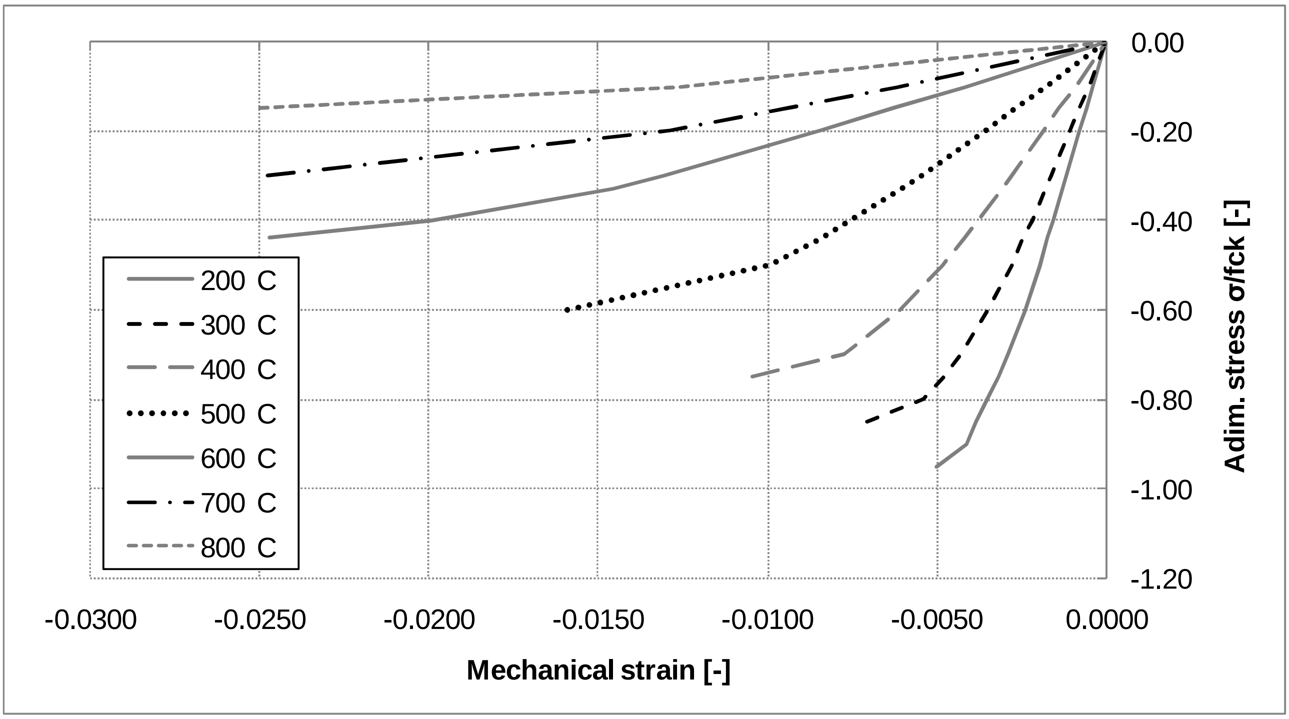

Figure 13 : Transient test curves of the ETC model

III.3. Transient creep strain

The transient creep strain curves are obtained by difference between the mechanical strain curves and the instantaneous stress-strain curves.

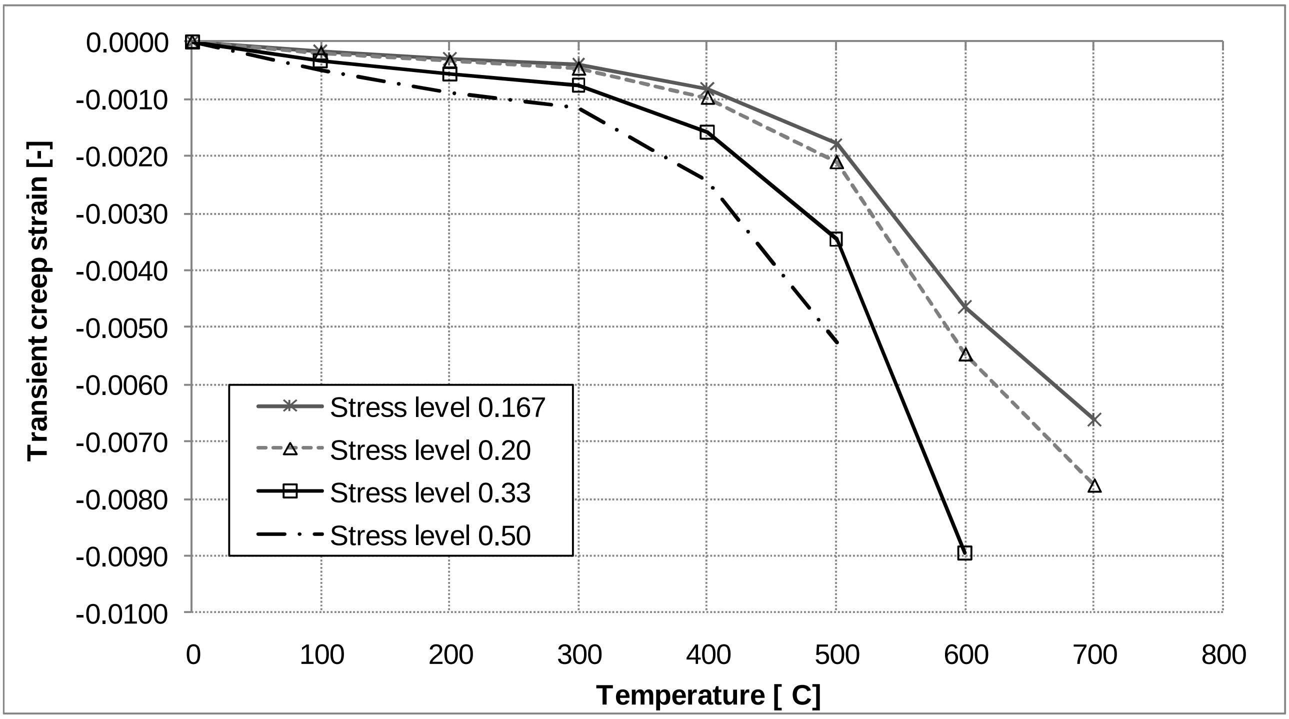

Figure 14 : Transient creep strain

III.4. Tests on structural elements

For the validation of the ETC concrete model on structural elements, please report to the following publications:

1. T. Gernay, “Effect of Transient Creep Strain Model on the Behavior of Concrete Columns Subjected to Heating and Cooling”, *Fire Technology*, accepted for publication, http://www.springerlink.com/content/3362rp1hv5355462/fulltext.pdf
2. T. Gernay, J-M Franssen, “A Comparison Between Explicit and Implicit Modelling of Transient Creep Strain in Concrete Uniaxial Constitutive Relationships”, *Proceedings of the Fire and Materials 2011 Conference*, San Francisco, pp. 405-416, 2011. http://hdl.handle.net/2268/76564
3. T. Gernay, J-M Franssen, “Consideration of Transient Creep in the Eurocode Constitutive Model for Concrete in the Fire situation”, *Proceedings of the Sixth International Conference Structures in Fire*, Michigan State University, pp. 784-791, 2010. http://hdl.handle.net/2268/18295