f

LIEGE UNIVERSITY

Urban & Environmental Engineering

Structural Engineering

USER'S MANUAL FOR SAFIR 2025

A COMPUTER PROGRAM FOR ANALYSIS OF STRUCTURES SUBJECTED TO FIRE

Part 5: material properties

by

Jean-Marc Franssen* & Thomas Gernay**

12/01/2026

* jm.franssen@uliege.be – Liege University, Liege, Belgium
** tgernay@jhu.edu – Johns Hopkins University, Baltimore, MD, U.S.A.

TABLE OF CONTENTS

I. INTRODUCTION

Table 1 shows an overview of the materials implemented in SAFIR®. Most commonly used materials in structural engineering are available for thermal and mechanical analyses, namely concrete, steel and wood. Several types of stainless steel, aluminum and high strength concrete (HSC) can also be used. Thermal properties of gypsum plaster boards have been implemented. In addition, it is possible to introduce other materials in a thermal analysis by specifying their thermal properties (either constant or temperature dependent), e.g., for insulation products.

Plane stress materials for steel and concrete are available for use with shell finite elements. Fully tridimensional mechanical models for steel and concrete are available for use with solid finite elements.

The software is designed to easily accommodate new constitutive models, so the intention is to continue expanding this library to introduce new materials.

Table 1. Materials available in SAFIR®

	THERMAL ANALYSIS		**STRUCTURAL ANALYSIS**		
Type of FE	2D Solid	3D Solid	Beam Truss	Shell	3D Solid
Type of law			Uniaxial	Plane stress	Triaxial
Mapped with	Beam Shell	3D Solid	/	/	/
Material:					
Steel	X	X	X	X	X
Concrete	X	X	X	X	X
Wood	X	X	X		
HSC	X	X	X		
Stainless steel	X	X	X		
Aluminum	X	X	X		
Gypsum	X	X			
Insulation	X	X			
User	X	X			

II. THERMAL

II.1. General

The temperature dependent thermal properties of the following materials have been programmed in the code:

- concrete
- carbon and stainless steel
- aluminum
- wood
- gypsum plaster boards

For concrete, steel and wood, the thermal models are based on the corresponding Eurocodes.

The thermal algorithm is based on the computation of the enthalpy. Use of the enthalpy formulation, instead of the specific heat, makes the software much more stable in cases where the specific heat curve shows sudden and severe variations as is the case, for example, in gypsum or with the evaporation of moisture.

Parameters to be introduced for all materials are the coefficient of convection on heated surface and the one on unheated surface (W/m^2K) plus the emissivity (-).

The coefficient of convection on heated surface recommended by Eurocode EN1991-1-2 is 25 W/m^2K for standard time-temperature curves. It is 35 W/m^2K for natural fire models. It is 50 W/m^2K for the hydrocarbon curve. For unheated surfaces, the recommended value in Eurocode is 4 W/m^2K when it does not contain the effects of heat transfer by radiation.

The emissivity is recommended in EN1991-1-2 as 0.8, unless a different value is given in the material related fire design parts of Eurocode. For concrete and carbon steel, Eurocodes EN1992-1-2 and EN 1993-1-2 recommend an emissivity of 0.7.

Additional inputs may be required for some of the materials. More detailed information is given hereafter.

II.2. Concrete

For **concrete** materials, the additional parameters may include the type of aggregate (siliceous or calcareous), the specific mass of concrete including water content (kg/m³), the free water content (kg/m³), and a last parameter that allows tuning the thermal conductivity between the lower limit and the upper limit (see clause 3.3.3 of EN 1992-1-2). The thermal model for normal strength concrete (NSC) and high strength concrete (HSC) is identical. The specific heat of the dry material and variation of specific mass are according to clause 3.3.2 of EN 1992-1-2. The evaporation of moisture is considered in the enthalpy formulation (the energy dissipated by the evaporation is released at a constant rate from 100 to 115°C, and then the energy release rate is linearly decreasing from 115 to 200°C), but the subsequent movements and participation in the heat balance of vapor are neglected.

During cooling, there is no re-condensation of the water and the thermal conductivity is considered as not reversible and considered at the value of the maximum reached temperature.

For `SILCONC_EN` and `CALCONC_EN`, the user inputs the value of a parameter for thermal conductivity α, between 0 and 1. 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:

$$k(T) = k_{lower}(T) + \alpha\left(k_{upper}(T) - k_{lower}(T)\right) \qquad \text{with } \alpha \in [0,1].$$

Names of the materials:

- `SILCONC_EN`: siliceous concrete of EN1991-1-2: 2004
- `CALCONC_EN`: calcareous concrete of EN1991-1-2: 2004
- `CONCEN2020`: concrete of EN1991-1-2, version published in 2020.
- `LWCONC_EN`: lightweight concrete of EN1994-1-2: 2004

II.3. Steel

Carbon steel used for structural steel and for reinforcing bars have the same thermal properties, which follow the equations of Eurocode EN 1993-1-2.

They are considered as reversible during cooling in SAFIR.

Names of the materials:

- `STEELEC3EN` or `STEELEC2EN` (identical for thermal analysis)

Galvanized carbon steel has the same thermal behaviour as that of STEELEC3EN from EN1993-1-2, except that the emissivity of the former is set to 0.35 up to first heating to 500°C and then 0.7 for T > 500°C. Properties are considered as reversible during cooling, except that the emissivity remains at 0.7 if the temperature has exceeded 500°C as the galvanization is not recovered.

Names of the materials:

- `GALVASTEEL`

For **stainless steel**, the thermal properties of following stainless steels have been programmed according to Annex C of EN 1993-1-2: 1.4301, 1.4401, 1.4404, 1.4571, 1.4003, 1.4462 and 1.4311.

As regards the thermal properties, these stainless steels have all the same behavior (which is not the case for the mechanical properties).

Names of the materials:

- `SLS1.4301, SLS1.4401, SLS1.4404, SLS1.4571, SLS1.4003, SLS1.4462, SLS1.4311`

For **aluminum**, on the other hand, materials of series 5000 and 6000 that have been programmed differ by their thermal conductivity. The thermal properties follow the equations of EN 1999-1-2.

Names of the materials:

- `AL5083_O`
- `AL5083_H12`
- `AL6061_T6`
- `AL6063_T6`

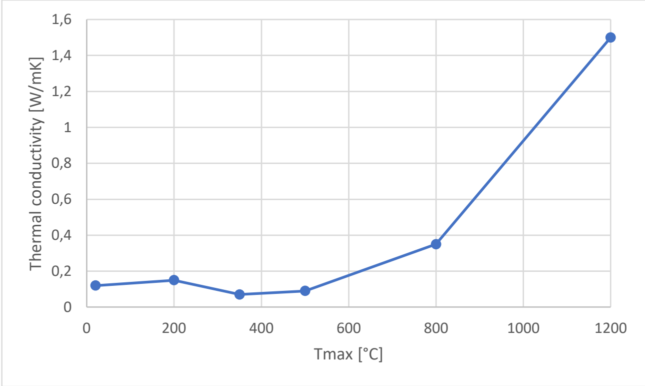
II.4. Wood

The behavior of **wood** is considered as purely conductive using modified thermal properties that represent complex phenomena, according to Annex B of EN 1995-1-2:2004 for '`WOODEC5`' or according to Section 8.5.2 of prEN 1995-1-2:2020 for '`WOOD2020`'.

Thermal conductivity is the same in both materials.

Temperature °C	Thermal conductivity $Wm^{-1}K^{-1}$
20	0,12
200	0,15
350	0,07
500	0,09
800	0,35
1200	1,50

a) values



b) graph

The specific mass and specific heat vary according to Annex B of EN 1995-1-2:2004 for '`WOODEC5`'

Table B2 – Specific heat capacity and ratio of density to dry density of softwood for service class 1

Temperature °C	Specific heat capacity $kJ\ kg^{-1}\ K^{-1}$	Ratio of density to dry density[a]
20	1,53	$1 + \omega$
99	1,77	$1 + \omega$
99	13,60	$1 + \omega$
120	13,50	1,00
120	2,12	1,00
200	2,00	1,00
250	1,62	0,93
300	0,71	0,76
350	0,85	0,52
400	1,00	0,38
600	1,40	0,28
800	1,65	0,26
1200	1,65	0

[a] ω is the moisture content

AC2

The specific mass and specific heat vary according to Section 8.5.2 of prEN 1995-1-2:2020 for ‘WOOD2020’

Table 8.1 - Temperature-dependent thermal properties for wood and the char layer

T [°C]	λ [W/mK] *except OSB, plywood*	λ [W/mK] *OSB, plywood*	c [kJ/kgK]	ρ/ρ_{20} [-]
20	0,12	0,12	1,53	1
99	*	*	1,77	1
100	*	*	13,60	1
120	*	*	13,50	1
121	*	*	2,12	0,89
200	0,15	0,15	2,00	0,89
250	*	*	1,62	0,83
300	*	*	0,71	0,68
350	0,07	0,07	0,85	0,46
400	*	*	1,00	0,34
500	0,09	0,19	*	*
600	*	*	1,4	0,25
800	0,35	0,74	1,65	0,23
1200	1,5	3,15	1,65	0

*linear interpolation may apply

NOTE: The values in Table 8.1 are calibrated with an initial moisture content for service class 2.

The specific heat is moisture dependent in both materials, but the values of Table B2 in EN1995-1-2:2004 are given for a service class 1 material which has a moisture content of 12% whereas the values of Table 8.1 in prEN1995-1-2:2020 are given for a service class 2 material which has a moisture content of 16%.

This leads, for a given moisture content, to slightly higher temperatures in WOOD2020 than in WOODEC5. Convergence, on the other hand, is easier with WOOD2020 because of the linear variation of specific heat from 99 to 100°C and from 120 to 121°C, whereas a step function is used at 99 and 120°C in WOODEC5.

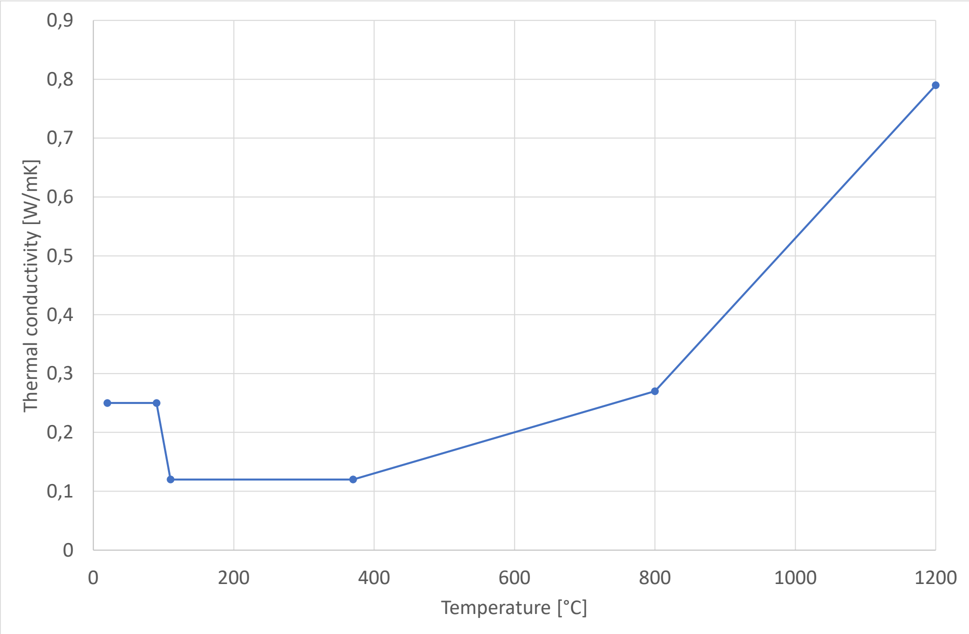
The direction of the grain is important as the conductivity is usually larger along the grain. In 2D analyses, most analyses are performed on the section of a beam or a column and the grain is perpendicular to the section, so the material is in fact isotropic in the plane of the section (in which the analysis is performed). However, if grain direction is in the direction of the section height for example, then the material is anisotropic if the ratio *r* is not equal to 1.

The thermal properties (conductivity, specific heat, density) are not reversible during cooling; they keep the values corresponding to the maximum reached temperature.

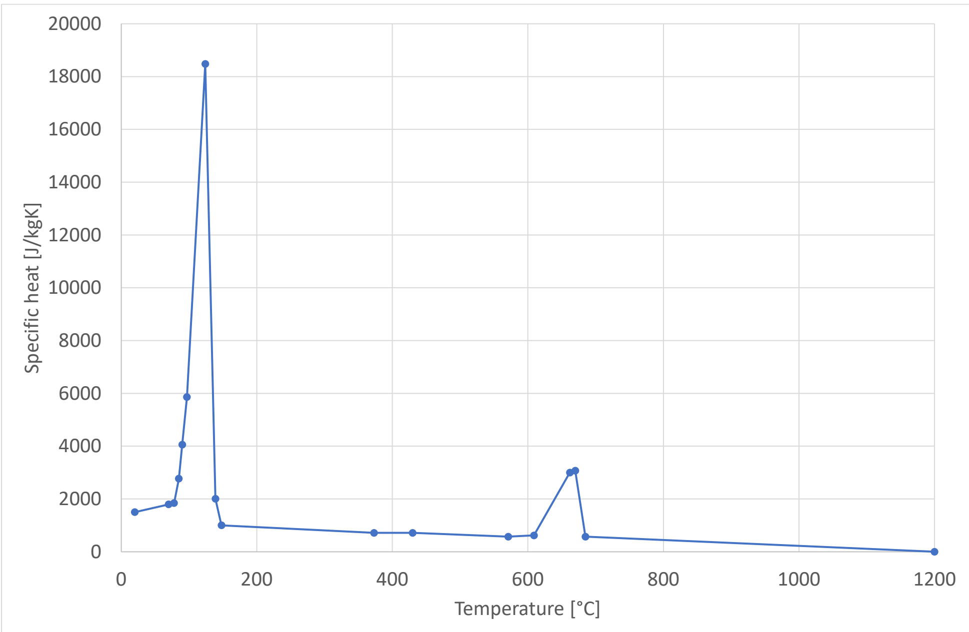
II.5. Gypsum and insulating materials

For **gypsum**, the properties have been adopted from Cooper (1997). Two materials are programmed in the code, for Type C and Type X boards, respectively. The two materials only differ by their density at 20°C:

- ✓ 732 kg/m³ for Type C
- ✓ 648 kg/m³ for Type X



Thermal conductivity of gypsum



Specific heat of gypsum

The relative value of the specific mass drops from 1.000 at 70°C to 0.825 at 90°C.

Gypsum type materials may lead to a slow convergence of the iterations during the time integration process because of the various peaks in the curve of equivalent specific heat. Therefore, a time step as small as 1 second may be required. When using the comeback strategy, this can be automatically addressed by specifying an appropriately small minimum time step.

Names of the materials:

- X_GYPSUM : 20°C density of 648 kg/m³
- C_GYPSUM : 20°C density of 732 kg/m³

One material with constant thermal properties, named "**insulation**", can be used. Parameters to be introduced are the thermal conductivity (W/mK), the specific heat (J/kgK), the specific mass of the dry material (kg/m³), the water content (kg/m³), the temperature Tstart at which evaporation starts (°C), and the temperature Tend at which evaporation ends (°C). The latter can be taken respectively as Tstart=100°C and Tend=120°C, for example. Reducing the spread between Tstart and Tend leads to more pronounced plateau in the evolution of the temperature but slows down convergence.

- INSULATION : constant thermal properties

SFRM_PROBA is an insulation material with temperature-dependent thermal properties. The thermal properties are based on a probabilistic model calibrated on a NIST study of 3 sprayed fire resistive materials. The details of the probabilistic formulation are taken from: Khorasani N.E., Gardoni P., Garlock M. (2015). "Probabilistic fire analysis: material models and evaluation of steel structural members". JSE, 141(12).

The thermal conductivity, specific heat, and density are temperature dependent. A logistic equation is coded in SAFIR for each of these properties. The user inputs the value of the standard normal parameter ε for the probabilistic evaluation of the temperature-dependent thermal conductivity, specific heat, and density. A positive (resp. negative) value leads to a value of the parameter higher (resp. lower) than the average measured experimentally. Note that a run of the computation with SAFIR with a given set of inputs for the ε is deterministic. To use the law in a probabilistic assessment, multiple runs are conducted where the values for ε for each run are drawn from a distribution, and this drawing of the values is performed outside of SAFIR.

- SFRM_PROBA : temperature-dependent thermal properties based on statistics for SFRM

II.6. User-defined materials

Up to five **user-defined materials** with either constant or temperature dependent thermal conductivity, specific heat and specific mass can be used. The properties are specified at a certain number of temperatures and linear interpolation is made for intermediate temperatures. The properties can be defined by the user as reversible, meaning that their values only depend on the current temperature, be it during heating or cooling; or as irreversible, in which case during cooling from a maximum temperature T_{max}, the properties will keep the value that was valid for T_{max}. The water content has to be given at the first defined temperature only. The energy dissipated by evaporation of the water is considered in the enthalpy formulation using the same method as for concrete material.

Parameters to be introduced are the first temperature T at which thermal properties are provided (°C), the thermal conductivity at T (W/mK), the specific heat at T (J/kgK), the specific mass of the dry material at T (kg/m³), the water content (kg/m³), the temperature Tstart at which evaporation starts (°C), the temperature Tend at which evaporation ends (°C), and a parameter to specify whether properties are reversible in cooling.

Names of the materials:

- `USER1`, `USER2`, .., `USER5` : user-defined temperature dependent thermal properties

III. STRUCTURAL

The constitutive relationships of the materials are based on the strain decomposition model of Equation 1.

$$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{\sigma} + \varepsilon_{tr} + \varepsilon_{i} \quad (1)$$

with ε_{tot} the total strain, obtained from spatial derivatives of the displacement field;

ε_{th} the thermal strain, dependent only on the temperature;

ε_{σ} the stress related strain, that contains the elastic and plastic parts of the strain;

ε_{tr} the transient creep, a particular term that appears during first heating under load in concrete;

ε_{i} an initial strain that can be used either for initial prestressing or for the strain that exists in in situ concrete when it hardens at the moment when loads already exist in the structure.

III.1. Uniaxial laws

Predefined uniaxial material models are coded for the temperature-dependent mechanical behavior of concrete, steel (carbon and stainless), wood and aluminum materials. The uniaxial models are to be used with truss and beam finite elements, as well as for reinforcing bars in shell finite elements.

III.1.1. Concrete

The concrete models are based on the laws of EN 1992-1-2. Parameters to be introduced are the aggregate type (siliceous or calcareous), the Poisson's ratio, the compressive strength and tensile strength. In addition, the user can select if the transient creep (see Eq. 1) is treated implicitly or explicitly in the model. The implicit formulation corresponds strictly to the current Eurocode model. The explicit formulation is a refinement of the model which is calibrated to yield the same response as the current Eurocode model in purely transient situation (which is the situation considered in the Eurocode model), but which, in addition, is able to take into account the non- reversibility of transient creep strain when the stress and/or the temperature is decreasing (Gernay and Franssen, 2012), (Gernay, 2012). It must be stressed that, even with continuously increasing temperatures and constant external applied loads, the stresses in part of a concrete section will decrease due to differential thermal expansions. Therefore, the explicit formulation is recommended in any case.

During cooling, the mechanical properties of strength and strain at peak stress are not reversible. An additional loss of 10% of the concrete compressive strength with respect to the value at maximum reached temperature is considered during cooling, as prescribed in EN 1994-1-2. A residual thermal expansion or shrinkage is considered when the concrete is back to ambient temperature, the value of which is taken as a function of the maximum temperature according to experimental tests published in the literature, see (Franssen, 1993).

The Young modulus is calculated based on the compressive strength and the strain at peak stress at each temperature. For the explicit models, it is given by: $E = 2 \times f_{c,T} / \varepsilon_{c1,ETC,T}$, where $\varepsilon_{c1,ETC,T}$ is the instantaneous stress-related strain at peak stress (not including transient creep). For the implicit models, the modulus is equal to: $E = 1.5 \times f_{c,T} / \varepsilon_{c1,T}$, where $\varepsilon_{c1,T}$ is the mechanical strain at peak stress (including transient creep).

Model	T (°C)	20	100	200	300	400	500	600	800
Explicit	$\varepsilon c1,ETC,T$	0.0025	0.0030	0.0038	0.0050	0.0063	0.0087	0.0127	0.0140
Implicit	$\varepsilon c1,T$	0.0025	0.0040	0.0055	0.0070	0.0100	0.0150	0.0250	0.0250

The names of the models are:
For normal strength concrete:

- `CALCON_ETC` : normal strength concrete, calcareous aggregates, explicit transient creep
- `SILCON_ETC` : normal strength concrete, siliceous aggregates, explicit transient creep
- `CALCONC_EN` : normal strength concrete, calcareous aggregates, implicit transient creep
- `SILCONC_EN` : normal strength concrete, siliceous aggregates, implicit transient creep

When using `CALCON_ETC / SILCON_ETC`, please cite:

> Gernay, T., Franssen, J.M. (2012). A formulation of the Eurocode 2 concrete model at elevated temperature that includes an explicit term for transient creep. *Fire Safety Journal*, 51, 1-9.

The user can also select between normal strength concrete (NSC) and high strength concrete (HSC). The only difference lies in the factors used for reduction of compressive strength with temperature. For HSC, these factors are as defined in Section 6 of EN 1992-1-2 for the three strength classes.

For high strength concrete:

- `CALHSC1ETC` : high strength concrete, class 1, calcareous, explicit transient creep
- `SILHSC1ETC` : high strength concrete, class 1, siliceous, explicit transient creep
- `CALHSC2ETC` : high strength concrete, class 2, calcareous, explicit transient creep
- `SILHSC2ETC` : high strength concrete, class 2, siliceous, explicit transient creep
- `CALHSC3ETC` : high strength concrete, class 3, calcareous, explicit transient creep
- `SILHSC3ETC` : high strength concrete, class 3, siliceous, explicit transient creep
- `CALHSC1_EN` : high strength concrete, class 1, calcareous, implicit transient creep
- `SILHSC1_EN` : high strength concrete, class 1, siliceous, implicit transient creep
- `CALHSC2_EN` : high strength concrete, class 2, calcareous, implicit transient creep
- `SILHSC2_EN` : high strength concrete, class 2, siliceous, implicit transient creep
- `CALHSC3_EN` : high strength concrete, class 3, calcareous, implicit transient creep
- `SILHSC3_EN` : high strength concrete, class 3, siliceous, implicit transient creep

For prestressed concrete:

- SILCONC_PR : prestressed concrete with siliceous aggregates
- CALCONC_PR : prestressed concrete with calcareous aggregates

A concrete material has been introduced to facilitate probabilistic structural fire analyses. The CACOPRBWE and SICOPRBWE materials have the same expression of stress-strain relationship as CALCON_ETC and SILCON_ETC , respectively, but the reduction factors for compressive strength with temperature are adopted from a Weibull distribution model calibrated on measured data. The user inputs the value of the standard normal parameter ε for the probabilistic evaluation of the temperature-dependent compressive strength. A positive (resp. negative) value leads, at each temperature, to a value of the strength higher (resp. lower) than the average measured experimentally for the corresponding temperature. Note that a run of the computation with SAFIR with a given value of ε is deterministic. To use the law in a probabilistic assessment, multiple runs should be conducted where the value for ε for each run are drawn from a distribution.

Probabilistic concrete:

- CACOPRBWE : same as CALCON_ETC with probabilistic compressive strength
- SICOPRBWE : same as SILCON_ETC with probabilistic compressive strength

When using CACOPRBWE and SICOPRBWE, please cite:

> Qureshi, R., Ni, S., Elhami Khorasani, N., Van Coile, R., Hopkin, D., Gernay, T. (2020). Probabilistic models for temperature-dependent strength of steel and concrete. *Journal of Structural Engineering*, 146(6), 04020102.

User-defined and "special" concrete:

- LWCONC_EN : lightweight concrete
- CALCONETCL : same as CALCON_ETC with user-defined loss of strength in cooling
- SILCONETCL : same as SILCON_ETC with user-defined loss of strength in cooling
- USER_CONC : user-defined concrete material

Concrete at room temperature

All concrete models mentioned above can be used at 20°C. Yet, it has to be noted that the material laws of EN1992-1-2 (fire part of Eurocode 2) when the temperature is equal to 20°C are not the same as those of EN1992-1-1 (Eurocode 2 at room temperature).

A uniaxial concrete model has been introduced in SAFIR which has the stress-strain relationship of EN1992-1-2. This model can be used with 2 different names, `CALCO_COLD` and `SILCO_COLD`.

It has to be understood that some phenomenon which are specific to concrete at room temperature, especially when used in the long term, are not taken into account by this model, e.g. creep and shrinkage.

The input data of this material are:

- ✓ the design value of the modulus of elasticity of concrete E_{cd} (in N/m²),
- ✓ the Poisson's ratio, used for calculation of torsion stiffness,
- ✓ the characteristic value of the compressive strength f_{ck} (in N/m²),
- ✓ the design value of the compressive strength f_{cd} (in N/m²),

Equation (3.15) from clause 3.1.6 (1)P of EN 1992-1-1 can be used to compute f_{cd} as a function of f_{ck} but the values of α_{cc} and γ_c must be chosen by the user.

Table 3.1 of EN 1992-1-2 and clause 3.1.3 (2) can be used to compute the value of E_{cm}, from which Equation (5.20) of clause 5.8.6 (3) can lead to the value of E_{cd} if the user has chosen the value of γ_{cE}.

The tensile strength is assumed to be 0.

The mean value of the compressive strength f_{cm} is computed according to Table 3.1 of EN1992-1-1 in which the values are in N/mm², although SAFIR uses N/m².

$$f_{cm} = f_{ck} + 8$$

The value of f_{cm} is used to compute the peak stress strain in compression according to Table 3.1.by:

$$\varepsilon_{c1} = 0.7 f_{cm}^{\ 0.31} \leq 2.8 \times 10^{-3}$$

The ultimate strain in compression is given according to Table 3.1.by:

$$\varepsilon_{\mathrm{cu1}} = 3.5 \times 10^{-3} \qquad \text{for } f_{cm} \leq 58 \text{ N/mm}^2$$

$$\varepsilon_{\mathrm{cu1}} = (2.8 + 27[(98 - f_{\mathrm{cm}})/100]^4 \times 10^{-3}) \qquad \text{for } f_{cm} > 58 \text{ N/mm}^2$$

The stress strain relationship in compression is given by equation (3.14) from clause 3.1.5 (1), together with clause 5.8.6 (3):

$$\frac{\sigma_c}{f_{cd}} = \frac{k\eta - \eta^2}{1 + (k-2)\eta}$$

with $$\eta = \varepsilon_c / \varepsilon_{c1}$$

and $$k = 1.05 E_{cd}\, \varepsilon_{c1} / f_{cd}$$

III.1.2. Steel

The steel models are based on the corresponding Eurocodes. Parameters to be introduced are the Young modulus, the Poisson's ratio and the yield strength. Two additional parameters are defined by the user to specify the behavior during cooling: the maximum temperature beyond which the behavior is not reversible during cooling (threshold) and the rate of decrease of the residual yield strength when the maximum temperature has exceeded the threshold (in MPa/K).

For structural carbon steel, the model (based on EN 1993-1-2) is elastoplastic with a limiting strain for yield strength (i.e. beginning of the descending branch with a negative stiffness) of 0.15 and an ultimate strain of 0.20.

- `STEELEC3EN` : structural carbon steel from EN 1993-1-2

A particular material has been introduced to represent the lower flange of cellular beams in composite floors. This lower flange was observed to exhibit lateral buckling in experimental tests. To model this behaviour, this material is similar to STEELEC3EN until 500°C, then it irrecoverably loses all strength and stiffness, linearly from 500°C to 600°C.

- `STEEL_WPB` : structural carbon steel from EN 1993-1-2, loses strength and stiffness from 500°C to 600°C.

For reinforcing carbon steel, the models for ductility class A, B and C (Figure 3.3 of EN 1992-1-2) with class N values for hot rolled and for cold worked steel (Table 3.2a of EN 1992-1-2) are available. The user inputs two additional parameters to specify the class of ductility and the fabrication process.
The value of the limiting strain $\varepsilon_{st,\theta}$ is 0.05 for ductility class A, 0.15 for class B and C.

- `STEELEC2EN` : reinforcing carbon steel from EN 1992-1-2

Prestressing steel of cold worked class B type (Table 3.3 of EN 1992-1-2) is also embedded in the code.

- `PSTEELA16` : prestressing steel of cold worked class B type from EN 1992-1-2

A uniaxial material for structural steel has been introduced for modeling slender steel sections with beam finite elements. This material has been developed to take into account local buckling based on the concept of effective stress. The stress-strain relationship from Eurocode 3 is adjusted in the compression part to take into account the effects of instabilities, for each combination of temperature-slenderness-support conditions (Franssen *et al*., 2014). Two additional parameters have to be introduced by the user: the slenderness and the number of supports of the plate where the material is present (3 supports for outstand plates such as flanges, 4 for internal plates such as webs). This material can be very useful when modeling large structures made of slender steel elements, for which a shell FE model would be too computationally expensive.

- `STEELSL` : structural carbon steel from EN 1993-1-2 with effective stress in compression

When using `STEELSL`, please cite:

Franssen, J. M., Cowez, B., Gernay, T. (2014). "Effective stress method to be used in beam finite

elements to take local instabilities into account". Fire Safety Science 11, 544-557.

A user defined steel material can also be used. It has the same general equation of stress-strain relationship as the structural steel from Eurocode but the user can choose the evolution of properties with temperature. Temperature dependent reduction factors for the Young modulus, yield strength and proportional strength, together with the thermal strain, are specified freely in a text file at specified temperatures. Linear interpolation is used between the specified temperatures.

- `USER_STEEL` : user defined steel with parametric stress-strain law from EN 1993-1-2

A steel material has been introduced to facilitate probabilistic structural fire analyses. The `STEC3PROBA` material has the same expression of stress-strain relationship as steel of Eurocodes but the reduction of yield strength with temperature follows a logistic EC3-based probabilistic model. The user inputs the value of the standard normal parameter ε for the probabilistic evaluation of the temperature-dependent yield strength. A positive (resp. negative) value leads, at each temperature, to a value of the strength higher (resp. lower) than the average measured experimentally for the corresponding temperature. Note that a run of the computation with SAFIR with a given value of ε is deterministic. To use the law in a probabilistic assessment, multiple runs should be conducted where the value for ε for each run are drawn from a distribution.

- `STEC3PROBA`: same as `STEELEC3EN` but with probabilistic yield strength reduction

When using `STEC3PROBA`, please cite:

Khorasani N.E., Gardoni P., Garlock M. (2015). "Probabilistic fire analysis: material models and evaluation of steel structural members". *JSE*, 141(12)".

For stainless steel, the mechanical properties of following stainless steels have been programmed according to Annex C of EN 1993-1-2: 1.4301, 1.4401, 1.4404, 1.4571, 1.4003, 1.4462 and 1.4311.

- `SLS1.4301`, `SLS1.4401`, `SLS1.4404`, `SLS1.4571`, `SLS1.4003`, `SLS1.4462`, `SLS1.4311` : stainless steels from Annex C of EN 1993-1-2

III.1.3. Aluminum

For aluminum, the mechanical properties follow the equations of EN 1999-1-2. The following different alloys and tempers have been programmed: 6061-T6, 6063-T6, 5083-H12, 5083-O.
Names of the materials:

- `AL5083_O`
- `AL5083_H12`
- `AL6061_T6`
- `AL6063_T6`

III.1.4. Wood

The constitutive model is by default elastic-brittle at all temperatures.

Since the version 2024 of SAFIR, an elastoplastic behavior in compression can be used. The user can specify (optional) the limit strain in compression. The constitutive model is elastic-brittle in tension and elastic-perfectly-plastic up to the specified limit strain in compression. The limit strain is the same at all temperatures. The input limit strain must be greater than the value of the elastic strain at compressive strength. If no value is input, the behavior is elastic-brittle also in compression.

Tensile and compressive strength as well as modulus of elasticity parallel to the grain vary with temperature according to Annex B of EN 1995-1-2:2004 for "`WOODEC5`", which is exactly the same as that of Section 8.6 in prEN 1995-1-2:2020 used for "`WOOD2020`", see Figure 1 from EN 1005-1-2:2004.

The mechanical properties are not reversible during cooling (they are function of the maximum temperature experienced). Since the version 2024 of SAFIR, a new material "`WOODECPF`" is available with properties partly reversible during cooling from temperatures lower than 300 °C, see below for additional information.

The thermal strain is null.

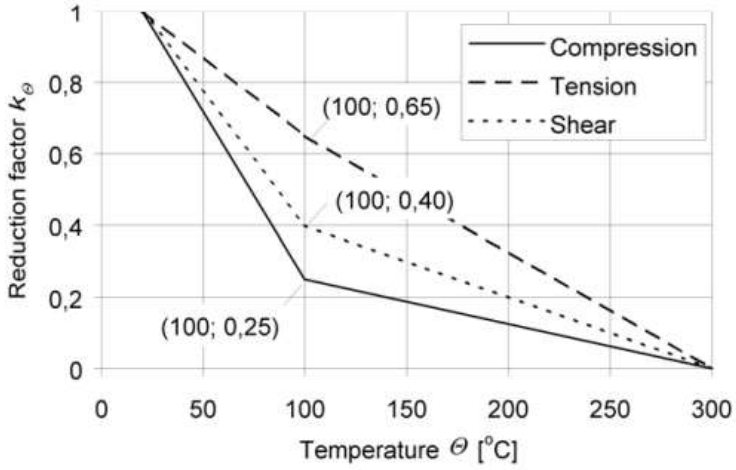


Figure B4 – Reduction factor for strength parallel to grain of softwood

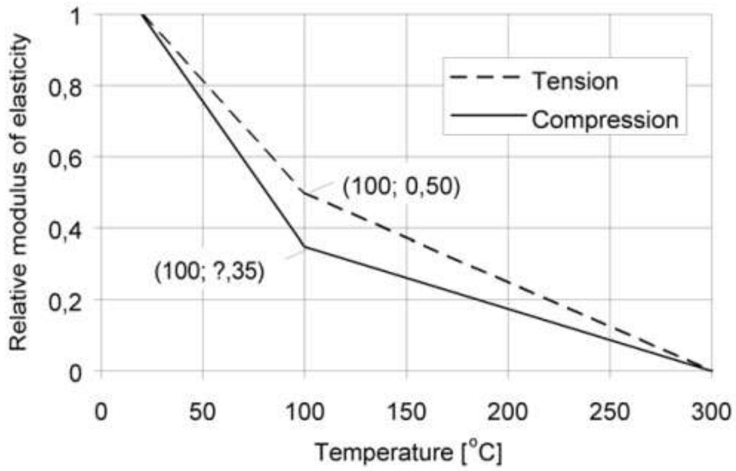


Figure B5 – Effect of temperature on modulus of elasticity parallel to grain of softwood

Figure 1 ; reduction of mechanical properties in wood

A wood material has been introduced to facilitate probabilistic structural fire analyses. The `WOODPRBWE` material has the same expression of stress-strain relationship as wood of Eurocode but the reduction factors for tensile and compressive strengths with temperature are adopted from a Weibull distribution model calibrated on measured data. The user inputs the value of the standard normal parameter ε for the probabilistic evaluation of the temperature-dependent strengths. A positive (resp. negative) value leads, at each temperature, to a value of the strengths higher (resp. lower) than the average measured experimentally for the corresponding temperature. Note that a run of the computation with SAFIR with a given value of ε is deterministic. To use the law in a probabilistic assessment, multiple runs should be conducted where the value for ε for each run are drawn from a distribution.

When using `WOODPRBWE`, please cite:

> Garcia-Castillo, Gernay, Paya-Zaforteza. (2023). "Probabilistic models for temperature-dependent compressive and tensile strengths of timber". *Journal of Structural Engineering ASCE*, 149 (2): 04022239

A wood material has been introduced to incorporate new experimental data on post-fire mechanical properties. The `WOODECPF` material has the same expression of stress-strain relationship and same reduction factors at elevated temperature as wood of Eurocode. However, during cooling, fibers that did not reach a temperatures of 300 °C partly recover their strength and modulus. A linear relationship is implemented between the Eurocode 5 value of retention factor at the peak temperature and a residual value at 20 °C based on experimental data. The details of the residual retention factors are given in the paper below.

When using `WOODECPF`, please cite:

> Zhao, Liu, Gernay, Chen, Zhao, Yang. (2024). "Investigation on the post-fire mechanical properties of glulam". *Construction and Building Materials.*

III.2. Biaxial (plane stress) laws

Predefined plane stress material models are embedded in the code for the temperature-dependent mechanical behavior of concrete and steel. These models are to be used with the shell finite element.

For concrete, the model is based on a plastic-damage formulation (Gernay *et al*. 2013). Plasticity is based on a Drucker Prager yield function in compression and a Rankine cut off in tension. Damage is formulated using a fourth-order tensor to capture the different damage processes in tension and compression including the effect of stress reversal on the concrete stiffness (crack closure). Transient creep is computed explicitly and not recovered during cooling. The variation of compressive and tensile strengths with temperature is according to EN 1992-1-2. The user selects the type of aggregate (calcareous or siliceous) and, in addition, inputs eight parameters: Poisson's ratio, compressive strength, tensile strength, strain at peak stress, dilatancy parameter, compressive ductility parameter, compressive damage at peak stress, tensile ductility parameter. These parameters allow calibrating the model on a specific type of concrete. For generic applications (when the concrete type is not known), predefined values of the parameters are suggested, see (Gernay and Franssen, 2015).

For steel, the model is elastoplastic with a Von Mises yield function and isotropic nonlinear hardening. Parameters to be introduced are the same as in the uniaxial situation. The variation of Young modulus, effective yield strength and proportional limit with temperature follow the EN 1993-1-2 and the hardening function is chosen to match as closely as possible the Eurocode uniaxial stress strain relationship.

Name of the materials:

- `CALCOETC2D`: NSC, calcareous, plastic-damage, explicit transient creep, EN 1992-1-2
- `SILCOETC2D`: NSC, siliceous, plastic-damage, explicit transient creep, EN 1992-1-2
- `STEELEC32D`: steel, elastoplastic Von Mises, isotropic nonlinear hardening, EN 1993-1-2
- `STEELCFS2D` : steel, elastoplastic Von Mises, isotropic tri-linear hardening-softening

When using `CALCOETC2D / SILCOETC2D`, please cite:

Gernay, T., Millard, A., Franssen, J. M. (2013). A multiaxial constitutive model for concrete in the fire situation: Theoretical formulation. *International Journal of Solids and Structures*, 50(22-23), 3659-3673.

III.3. Triaxial laws

Predefined fully triaxial stress material models are embedded in the code for concrete and steel, to be used with the solid finite element. These models are an extension of the plane stress models described in the previous section. They are based on the same assumptions and require the same input parameters as the plane stress model, with the only difference in the implementation lying in the number of stress and strain components at an integration point.

Name of the materials:

- `CALCOETC3D`: NSC, calcareous, plastic-damage, explicit transient creep, EN 1992-1-2
- `SILCOETC3D`: NSC, siliceous, plastic-damage, explicit transient creep, EN 1992-1-2
- `STEELEC33D`: steel, elastoplastic Von Mises, isotropic nonlinear hardening, EN 1993-1-2

When using `CALCOETC3D / SILCOETC3D`, please cite:

> Gernay, T., Millard, A., Franssen, J. M. (2013). A multiaxial constitutive model for concrete in the fire situation: Theoretical formulation. *International Journal of Solids and Structures*, 50(22-23), 3659-3673.

IV. SILCON_ETC - CALCON_ETC

IV.1. Introduction

This section 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*, Vol. 48, n°2, pp. 313-329 http://www.springerlink.com/content/3362rp1hv5355462/fulltext.pdf

T. Gernay, J-M Franssen, "A formulation of the Eurocode 2 concrete model at elevated temperature that includes an explicit term for transient creep", *Fire Safety Journal*, 51, pp. 1-9, 2012.
http://hdl.handle.net/2268/114050

Gernay, T., Millard, A., & Franssen, J. M. (2013). A multiaxial constitutive model for concrete in the fire situation: Theoretical formulation. *International Journal of Solids and Structures*, 50(22-23), 3659-3673. https://doi.org/10.1016/j.ijsolstr.2013.07.013

Nomenclature

T	Temperature
$Tmax$	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
$\varepsilon_{c1,EC2}$	Peak stress strain of Eurocode 2
$\varepsilon_{c1,ENV}$	Peak stress strain of ENV (minimum value)
$\varepsilon_{c1,ETC}$	Peak stress strain of ETC model
$\varepsilon_{c0,EC2}$	Strain to 0 stress of Eurocode 2
$\varepsilon_{c0,ETC}$	Strain to 0 stress of ETC model
fck	Compressive strength at 20°C
fc,T	Compressive strength (temperature-dependent)
ftk	Tensile strength at 20°C
ft,T	Tensile strength (temperature-dependent)
E_t	Tangent modulus
$\phi(T)$	Transient creep function
$E0$,ETC	Elastic modulus of the ETC model

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/m²]
PARACOLD(4,NM) Tensile strength f_{tk} [N/m²]

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 $\sigma^{(s-1)}$

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 $E_{t}^{(s)}$

IV.2. Description of the material law

IV.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:

- The temperature has increased between step (s) and step (s-1)
- The (converged) stress at time step (s-1) is a compressive stress
- 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.

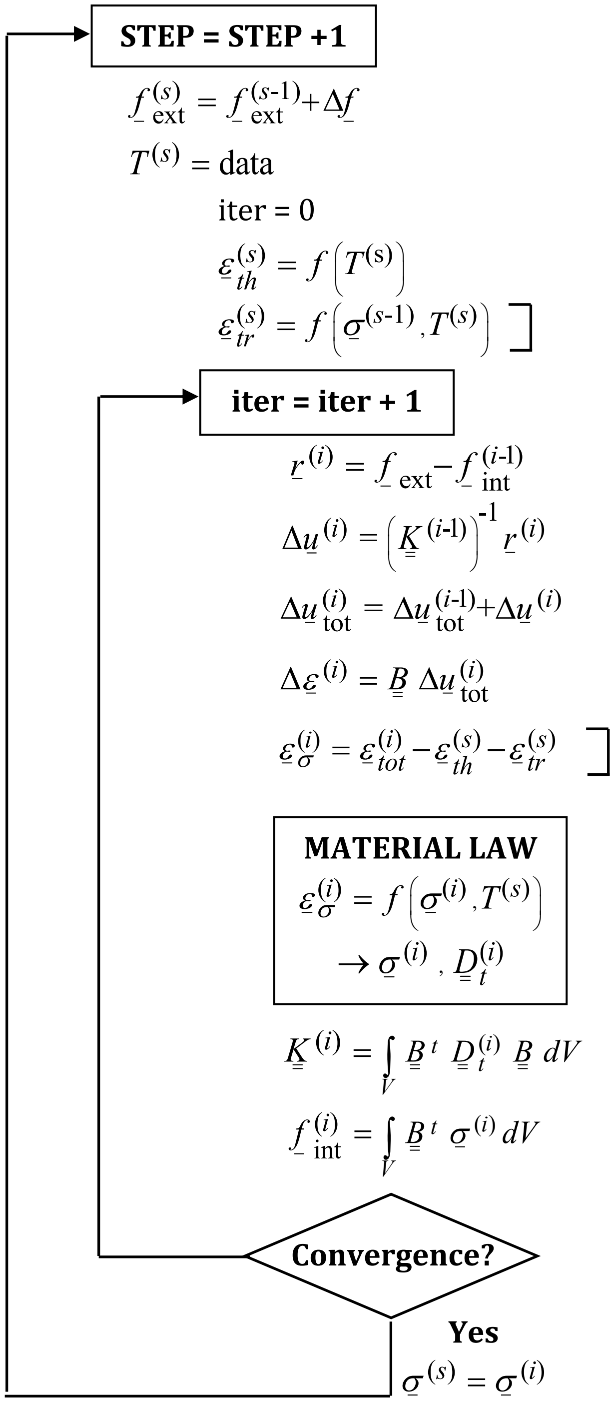


Figure 2 : Flow chart of the implementation of the ETC concrete model in SAFIR

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.

IV.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.

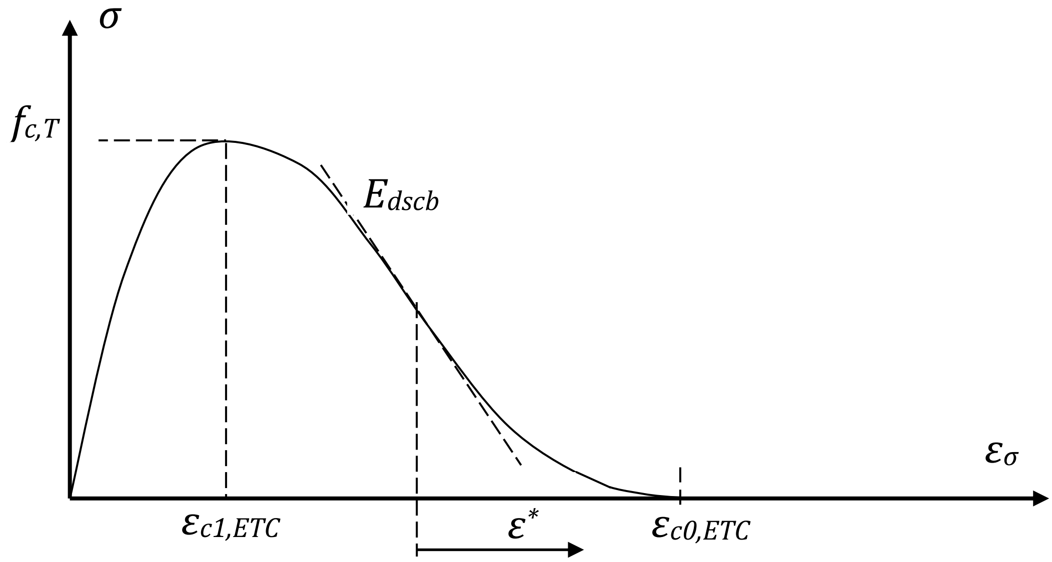


Figure 3 : ETC stress-strain relationship in compression

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 $\varepsilon^* \le 0$;

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

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

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

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

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

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

$$\sigma = 0$$

$$E_t = 0$$

Figure 4 present the (instantaneous) stress-strain curves in compression for the material

SILCON_ETC, for temperatures between 20°C and 1000°C.

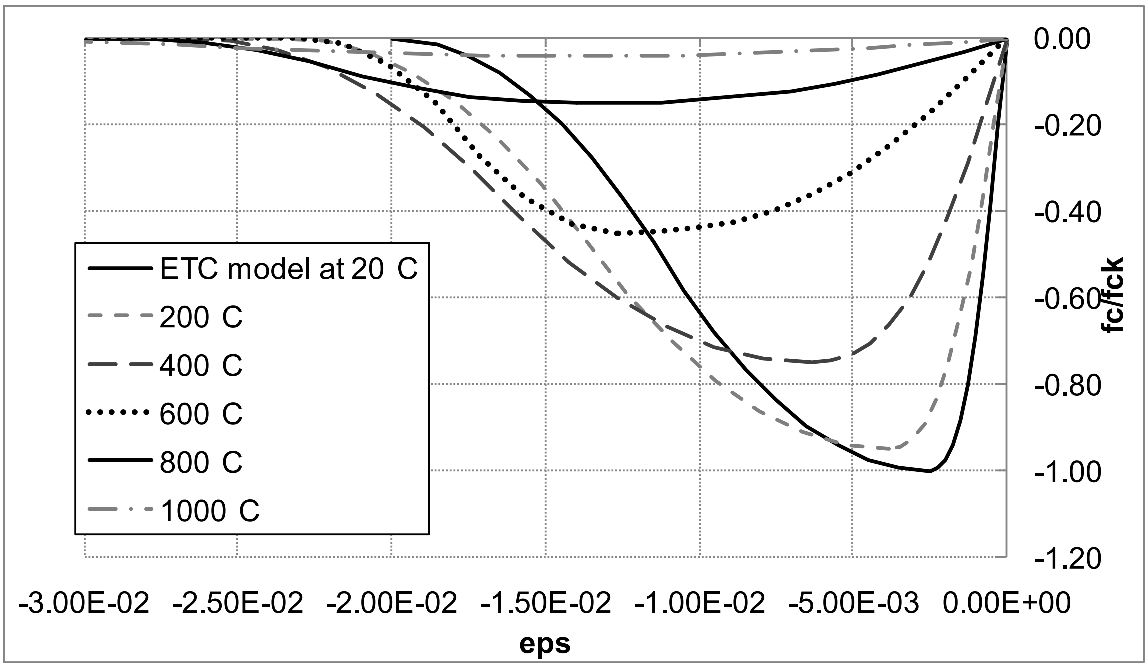


Figure 4: ETC concrete model in compression

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.

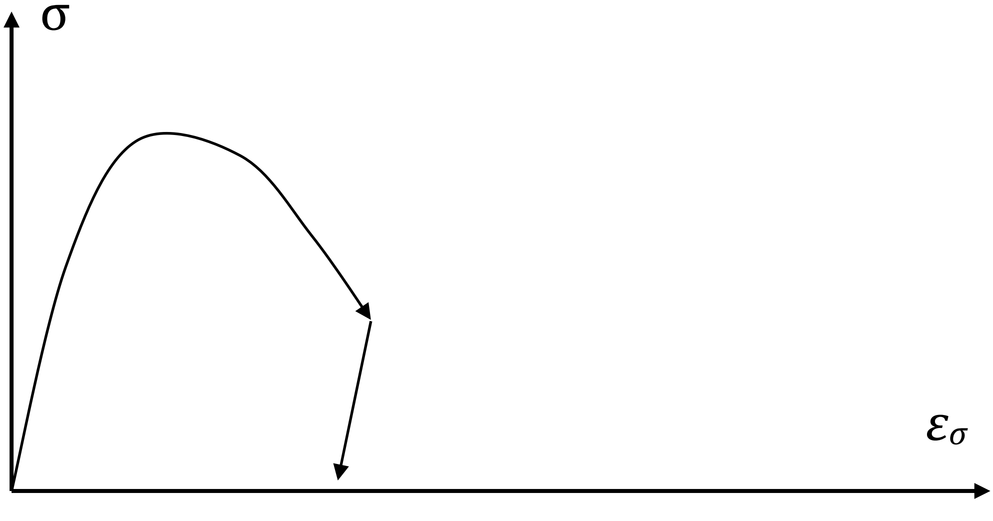


Figure 5 : Unloading in compression – plasticity model

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 7). 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.

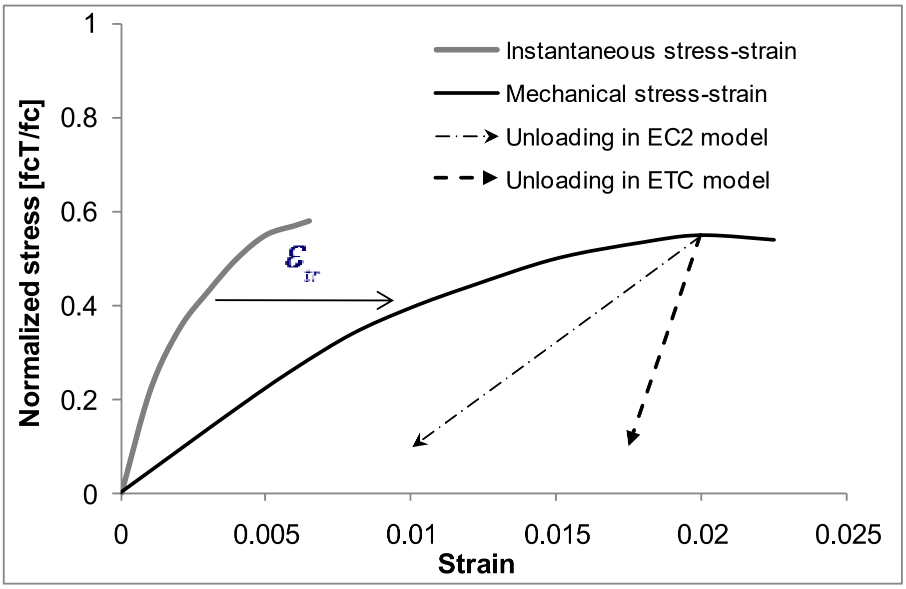


Figure 6 : Concrete behavior at 500°C

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.

IV.2.3. Concrete in tension

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.

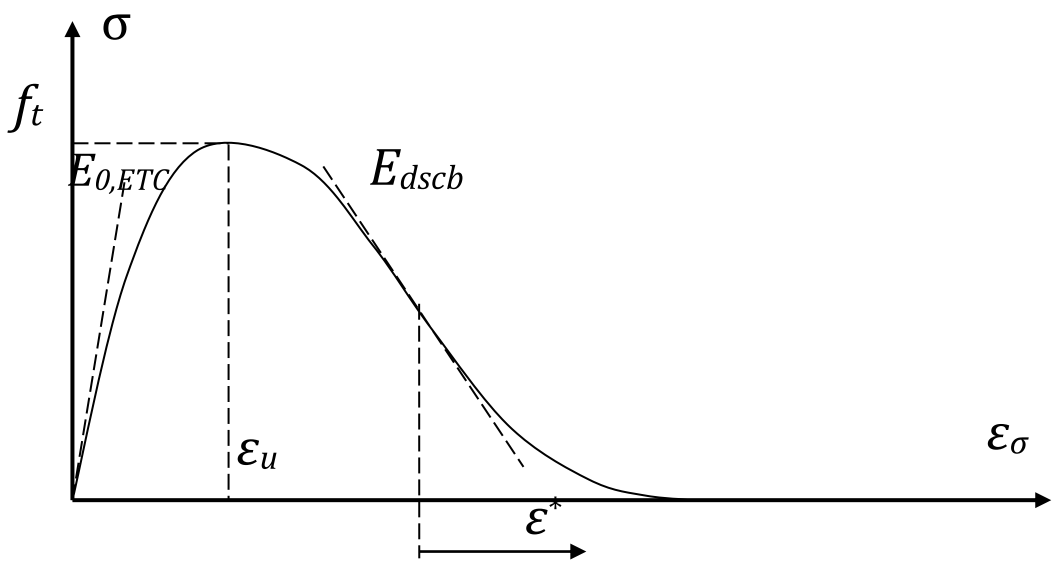


Figure 7 : ETC stress-strain relationship in tension

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 $\varepsilon_\sigma \le \varepsilon_u$:

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

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

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

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 $\varepsilon^* \le 0$;

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

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

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 8 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 9). 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.

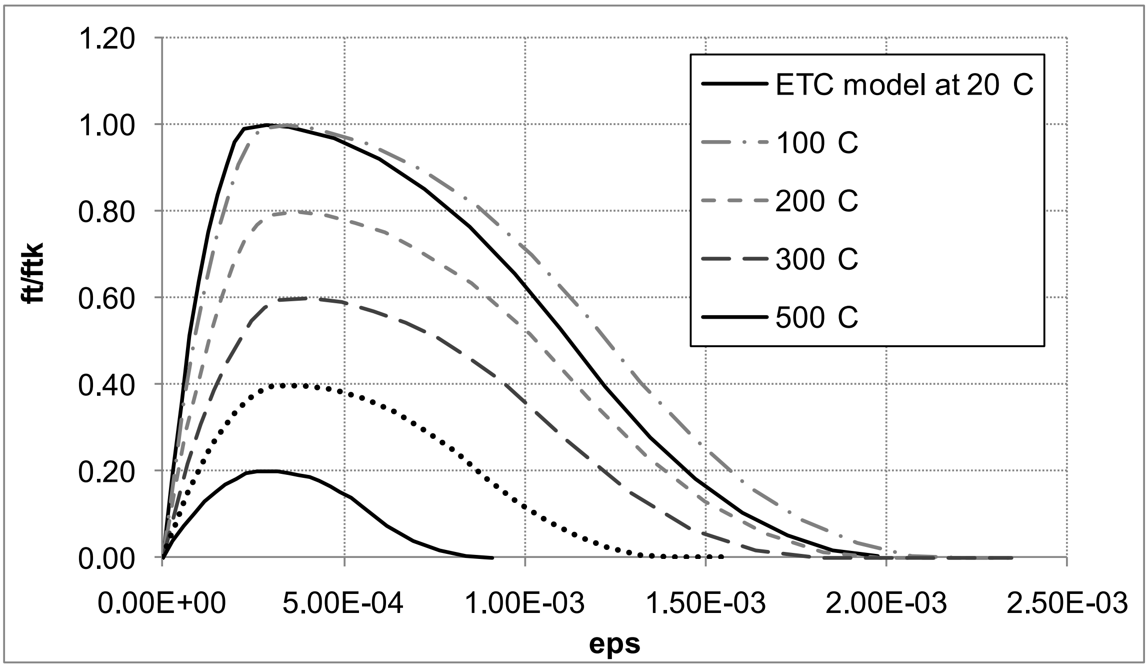


Figure 8 : ETC concrete model in tension

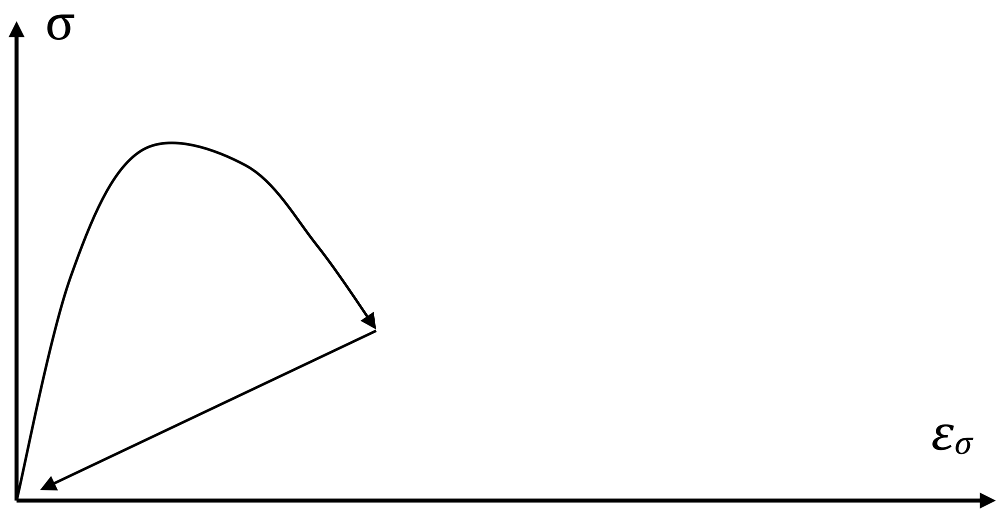


Figure 9 : Unloading in tension – damage model

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 $1/f_c$.

IV.2.4. Evolution laws of the material properties

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

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

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

$$f_t\left(T\right) = k_{ft}\left(T\right) . f_{tk}$$

The evolutions of $k_{fc}\left(T\right)$ and $k_{ft}\left(T\right)$ 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 10 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.

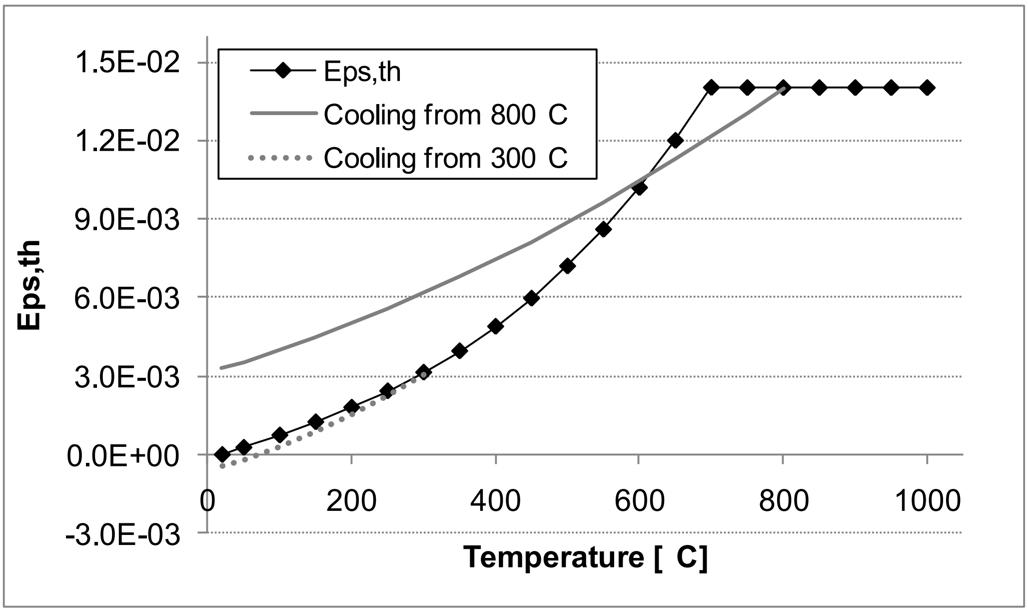


Figure 10 : Thermal strain implemented in the ETC concrete model

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

IV.3. 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.

IV.3.1. Instantaneous stress-strain curves

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

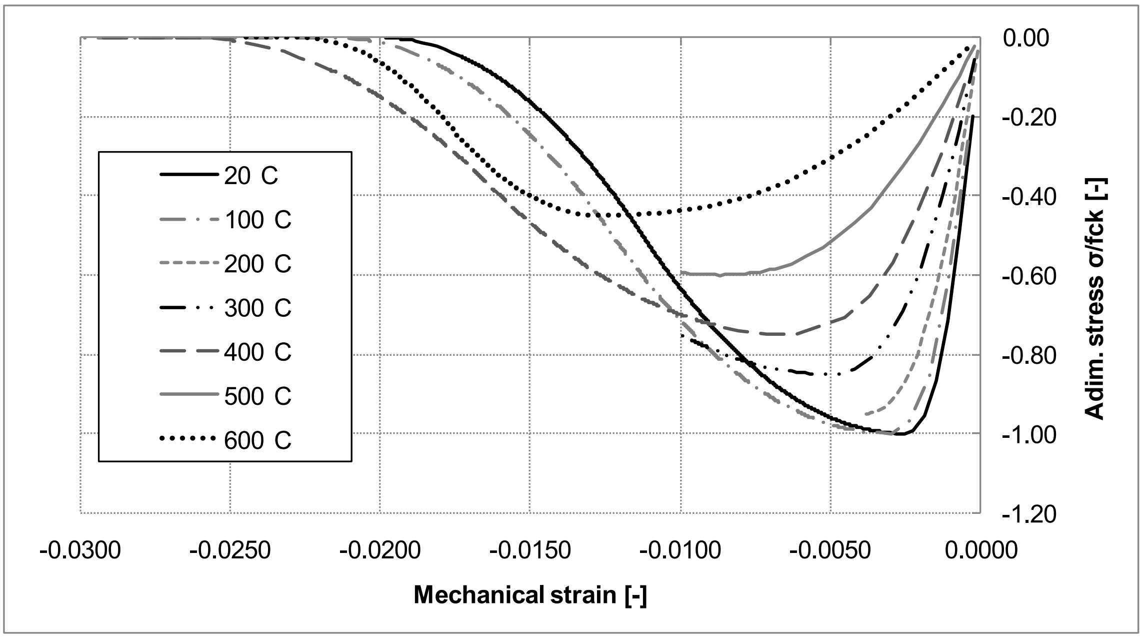


Figure 11 : ETC concrete model in compression

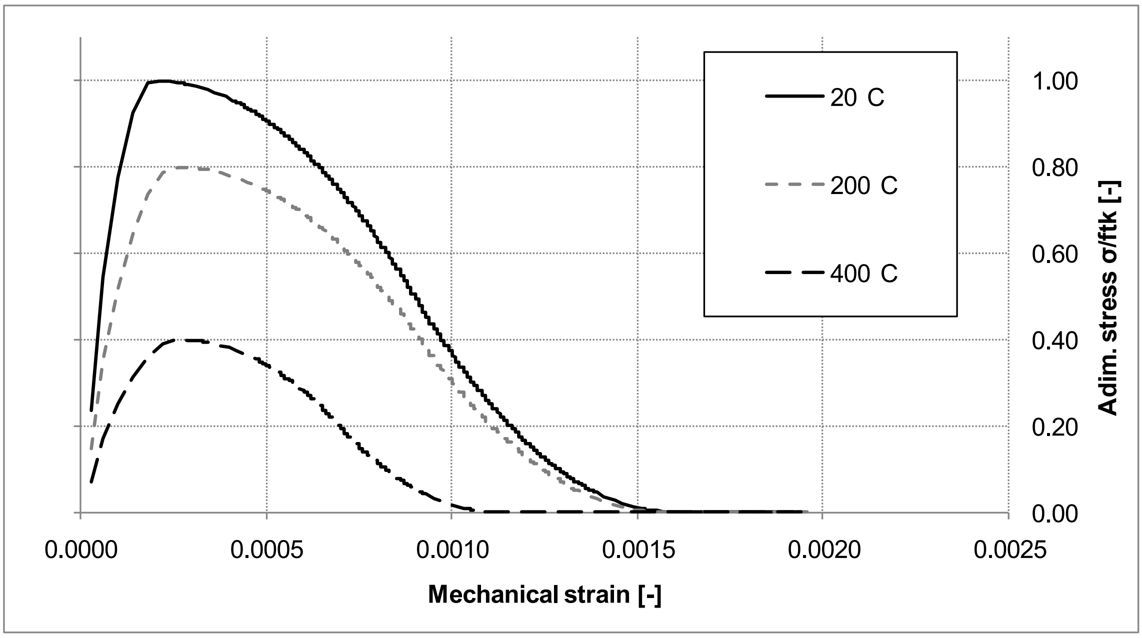


Figure 12 : ETC concrete model in tension

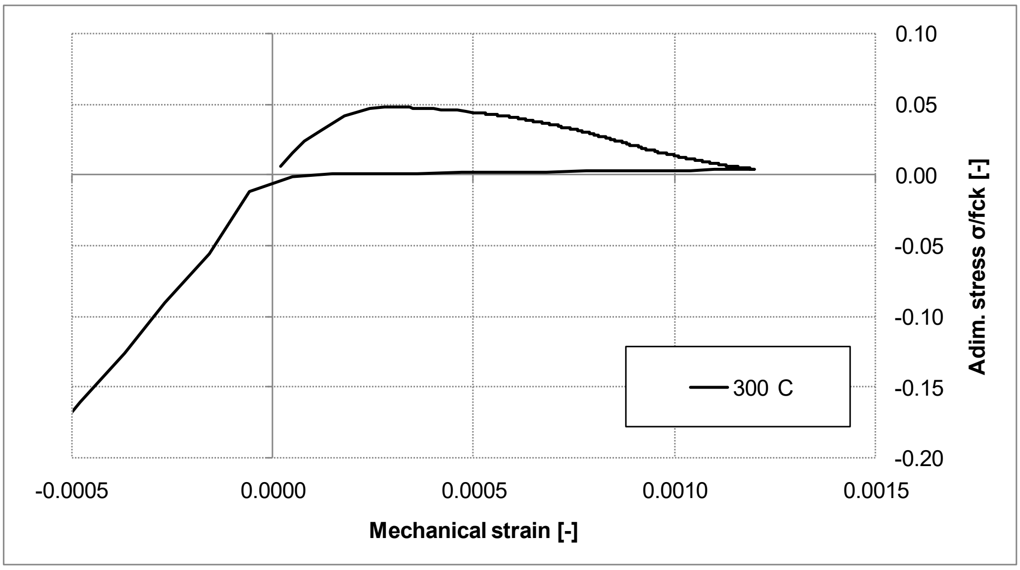


Figure 13 : Transition zone between tension and compression

IV.3.2. 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.

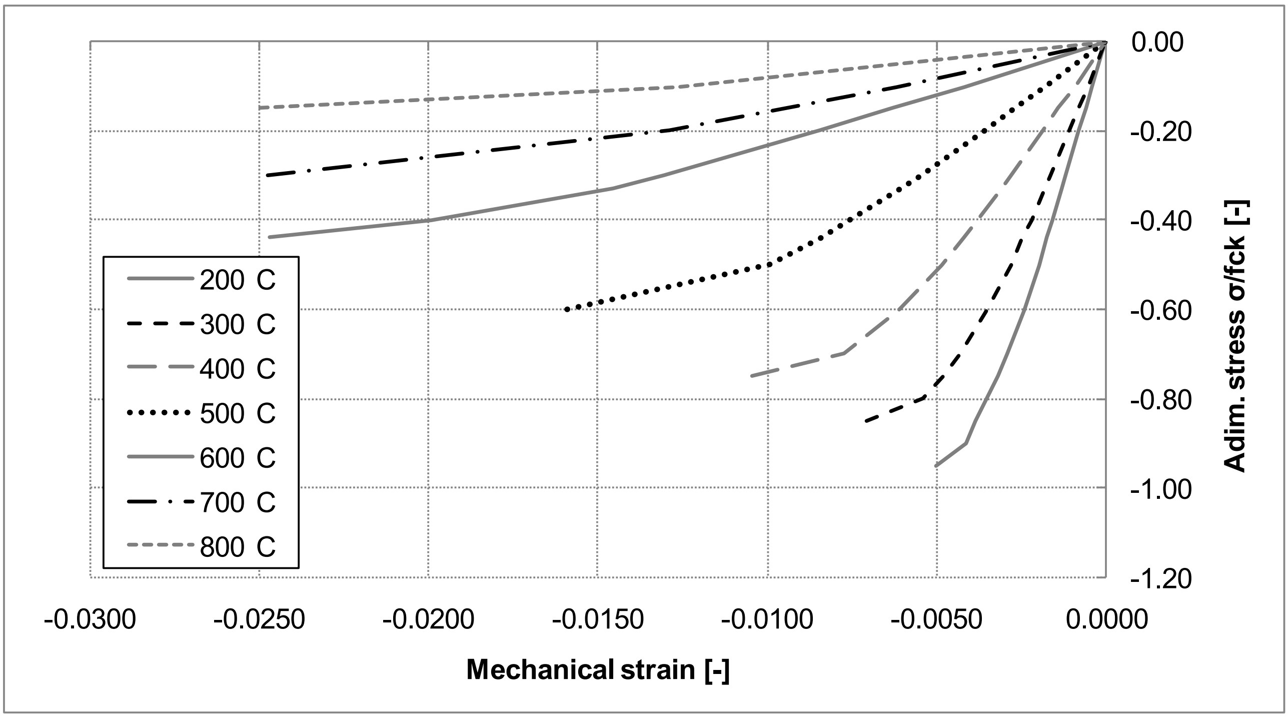


Figure 14 : Transient test curves of the ETC model

IV.3.3. Transient creep strain

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

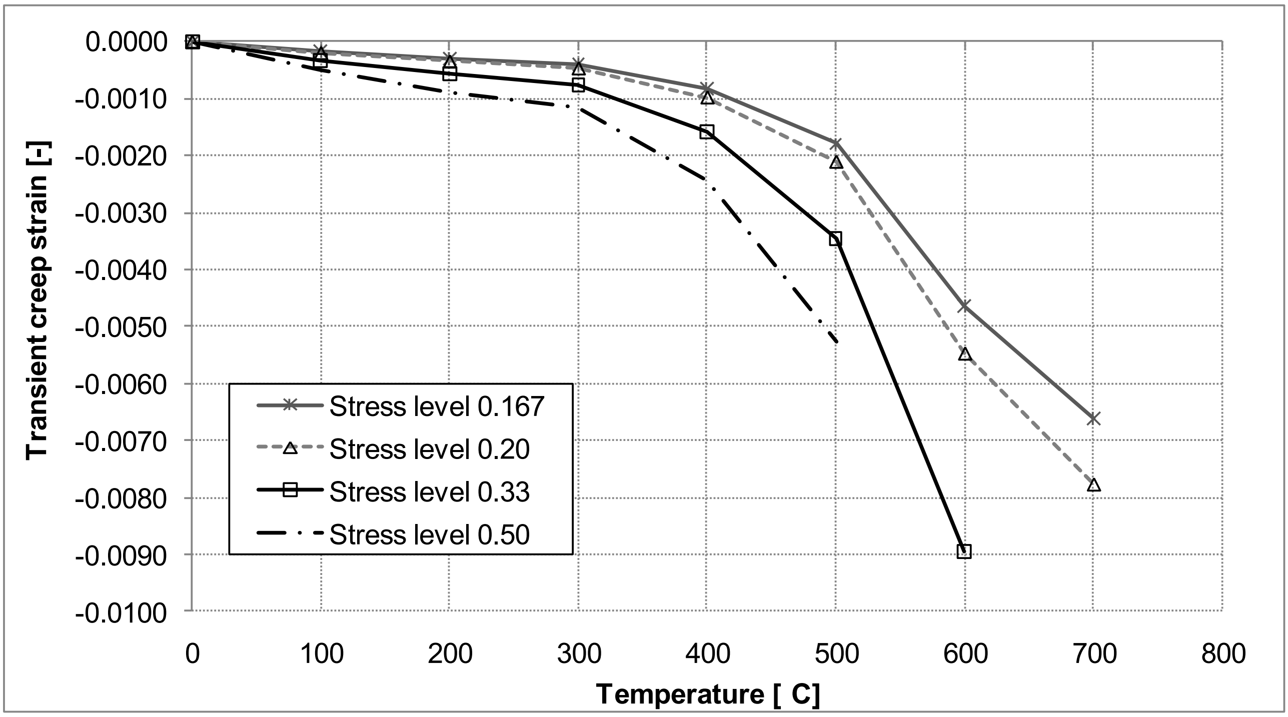


Figure 15 : Transient creep strain

IV.3.4. Tests on structural elements

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

1. Gernay, T., Franssen, J. M. (2015). A plastic-damage model for concrete in fire: Applications in structural fire engineering. *Fire Safety Journal*, 71, 268-278.

2. Gernay, T. (2012). Effect of transient creep strain model on the behavior of concrete columns subjected to heating and cooling. *Fire technology*, 48(2), 313-329.

3. Ni, S., Gernay, T. (2021). Considerations on computational modeling of concrete structures in fire. *Fire Safety Journal*, 120, 103065.

V. SILCONC_EN - CALCONC_EN

V.1. Introduction

This section describes the material models SILCONC_EN and CALCONC_EN, implemented in the software SAFIR. The material models SILCONC_EN and CALCONC_EN are the uniaxial constitutive models for concrete from the Eurocode 1992-1-2.

The SAFIR materials SILCONC_EN and CALCONC_EN are the material models from EN1992-1-2.

These models are uniaxial material laws for siliceous (SILCONC_EN) and calcareous (CALCONC_EN) concrete.

User input for thermal analysis

If CMAT(NM) = SILCONC_EN , CALCONC_EN - 6 parameters are required (1 line only)

PARACOLD(3,NM)	Specific mass	[kg/m³]
PARACOLD(5,NM)	Moisture content	[kg/m³]
PARACOLD(6,NM)	Convection coefficient on hot surfaces	[W/m²K]
PARACOLD(7,NM)	Convection coefficient on cold surfaces	[W/m²K]
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 $\alpha \in [0,1]$.

User input for mechanical analysis

If CMAT(NM) = SILCONC_EN , CALCONC_EN - 3 parameters are required (1 line only)

PARACOLD(2,NM)	Poisson ratio ν	[-]
PARACOLD(3,NM)	Compressive strength f_{ck}	[N/m²]
PARACOLD(4,NM)	Tensile strength f_{tk}	[N/m²]

V.2. Description of the material law

V.2.1. Concrete in compression

The behaviour of concrete in compression is described by a stress-strain relationship.
The 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.

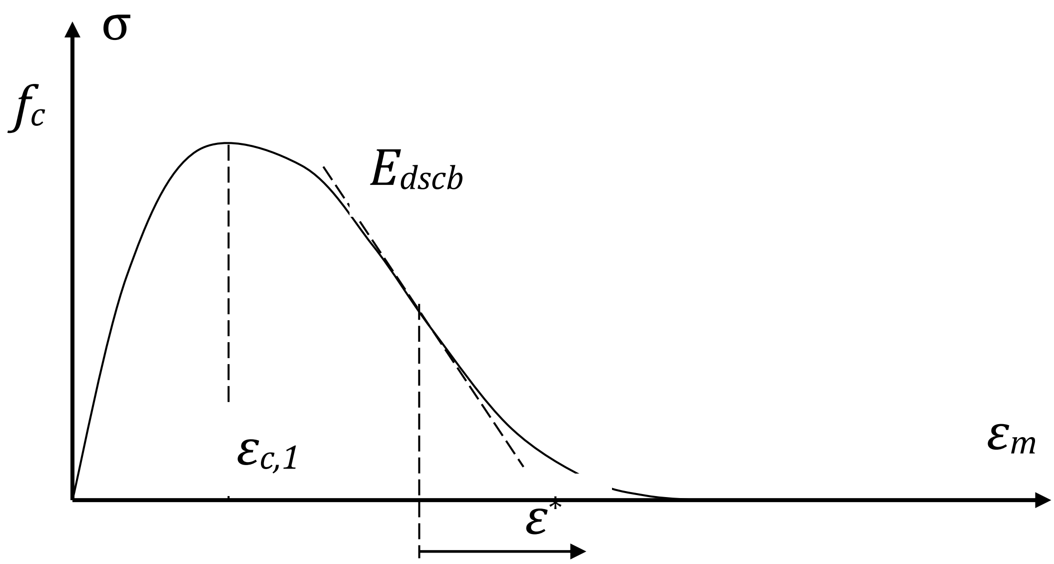


Figure 16 : Stress-strain relationship in compression

The ascending branch is characterized by the compressive strength f_c, and the strain at compressive strength $\varepsilon_{c,1}$. The equation that gives the stress σ and the tangent modulus are, for $\varepsilon_m \leq \varepsilon_{c,1}$:

$$\sigma = f_c \frac{3\frac{\varepsilon_m}{\varepsilon_{c,1}}}{2+\left(\frac{\varepsilon_m}{\varepsilon_{c,1}}\right)^3}$$

$$E_t = 6 f_c \frac{1-\left(\frac{\varepsilon_m}{\varepsilon_{c,1}}\right)^3}{\varepsilon_{c,1}\left[2+\left(\frac{\varepsilon_m}{\varepsilon_{c,1}}\right)^3\right]^2}$$

<u>Variation of the compressive strength with temperature</u>.
During heating, the compressive strength $f_c(T)$ of concrete that is at temperature T is calculated according to:

$$f_c(T) = k_{fc}(T).f_c(20)$$

The evolution of $k_{fc}(T)$ with temperature is illustrated in Figure 17, see § 3.2.2.1 in EN 1992-1-2.

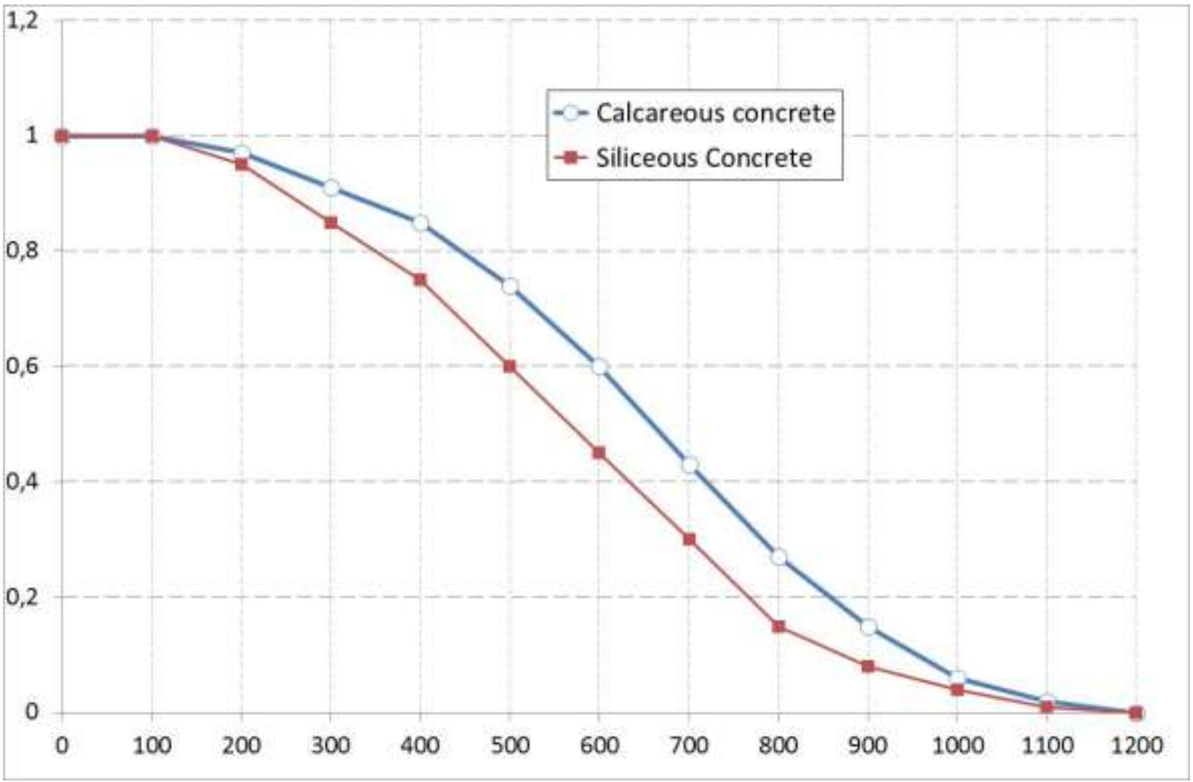


Figure 17: compressive strength of concrete

<u>Variation of the strain at compressive strength with temperature</u>.
The strain at compressive strength $\varepsilon_{c,1}$ is a function of the maximum temperature experienced by the material T_{max} as shown on Figure 18, see Table 3.1 in EN 1991-1-2.

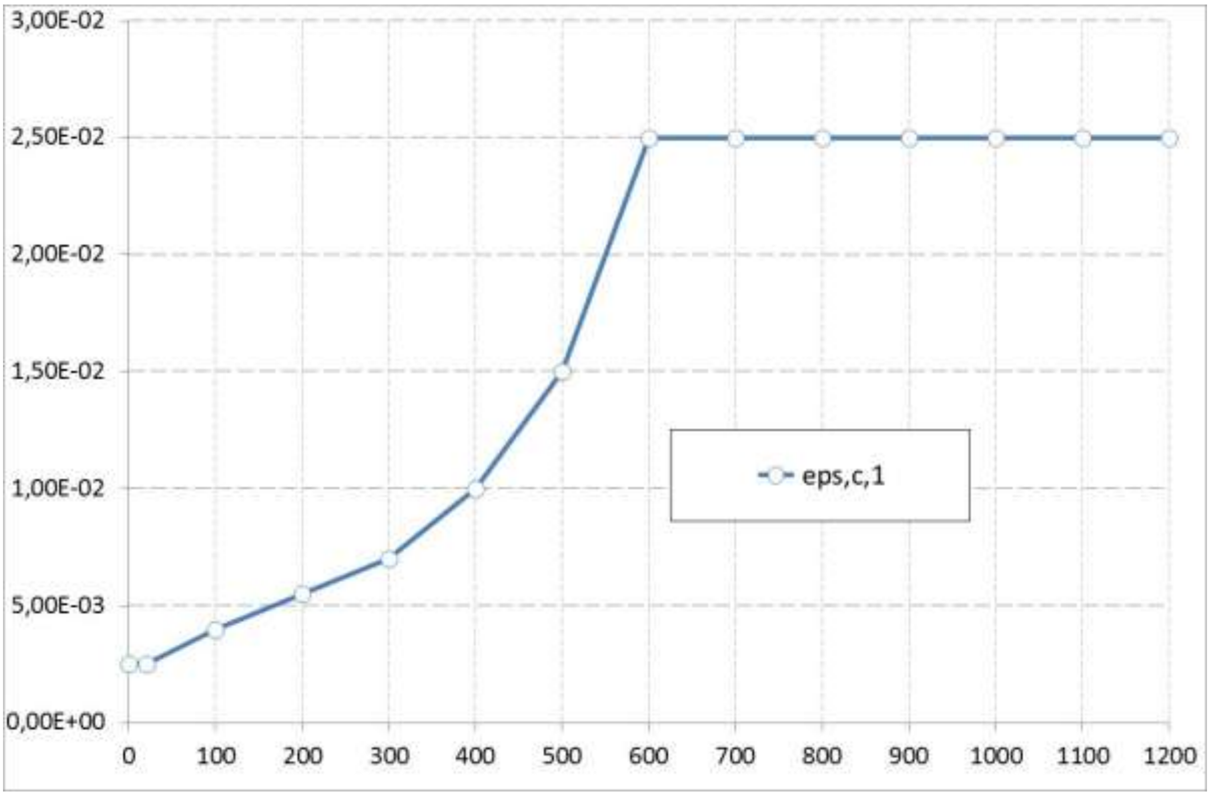


Figure 18: evolution of the strain at compressive strength with the maximum temperature

<u>Modulus at the origin E_0</u>

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:

$$E_0 = \frac{3}{2}\frac{f_c}{\varepsilon_{c,1}}$$

Figure 19 shows the evolution of the modulus at the origin as a function of the temperature during heating for concrete with a compressive strength at room temperature f_c equal to 30 and 60 MPa.

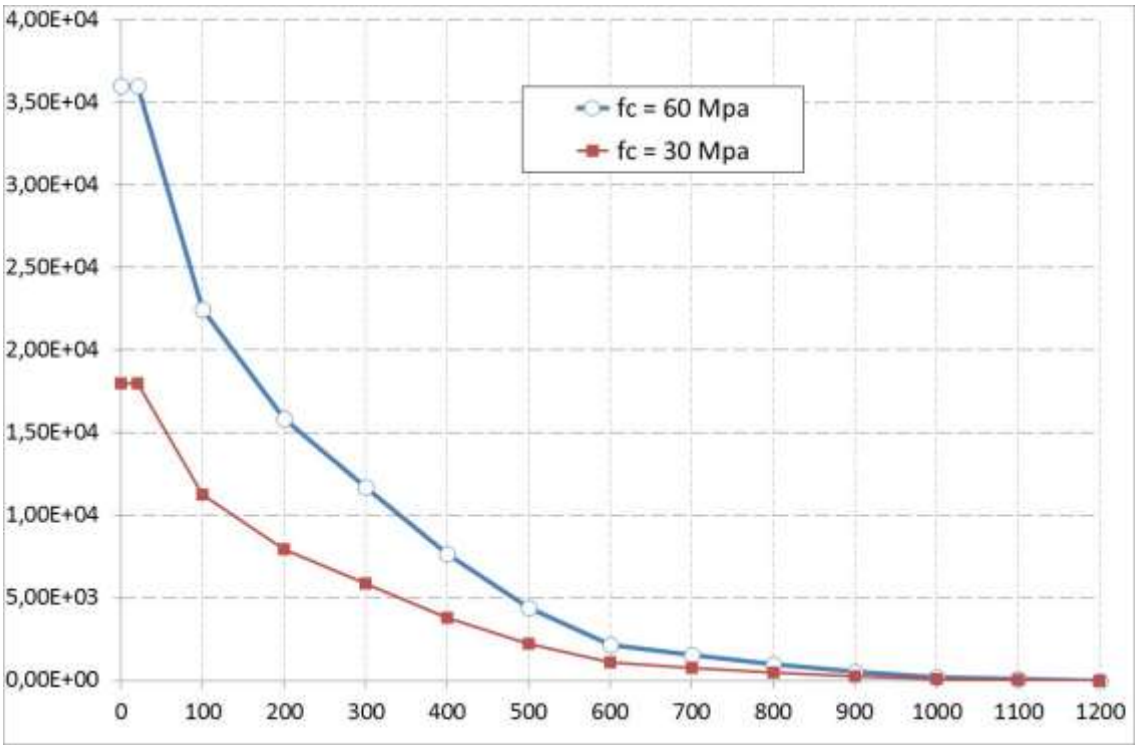


Figure 19: evolution of the modulus at the origin

The descending branch is made of two 3[rd] order polynomial from point (ε_{c1} ; f_c) until point (ε_{cu1} ; 0). Figure 20 shows the evolution of the strain at 0 strength ε_{cu1}, see Table 3.1 in EN 1991-1-2.

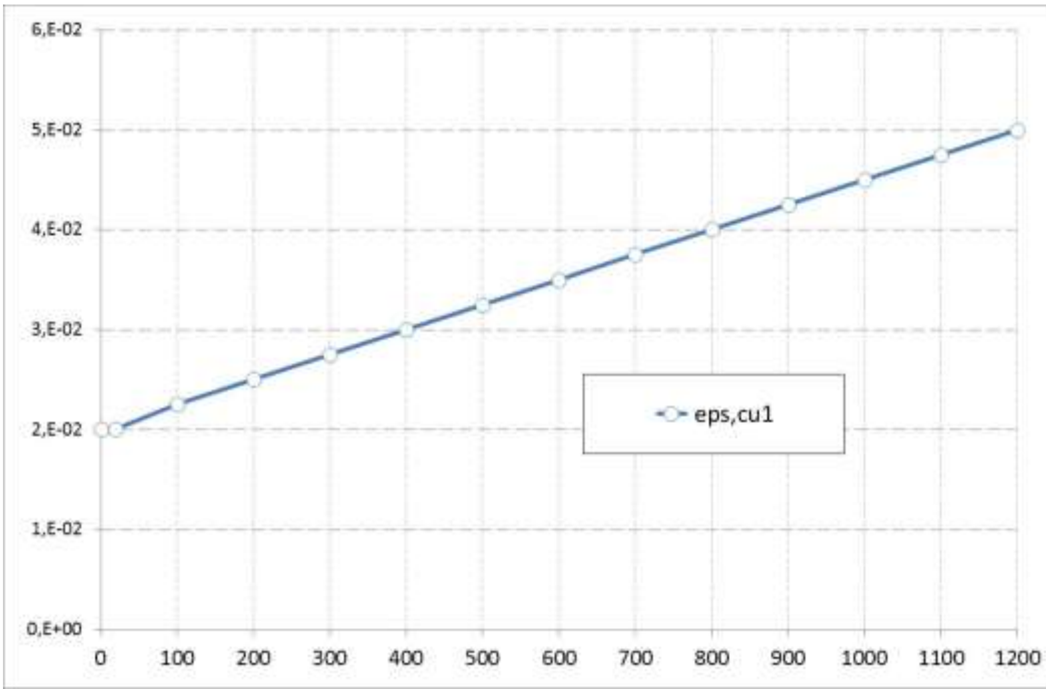


Figure 20: evolution of the strain at 0 strength

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:

$$E_{dscb} = 2\frac{f_c}{\varepsilon_{cu1} - \varepsilon_{c1}}$$

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

$$\varepsilon^* = \varepsilon_m - \varepsilon_u - f_c / E_{dscb}$$
$$\sigma^* = E_{dscb}\ \varepsilon^*$$

If $\varepsilon^* \leq 0$;

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

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

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

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

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

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.

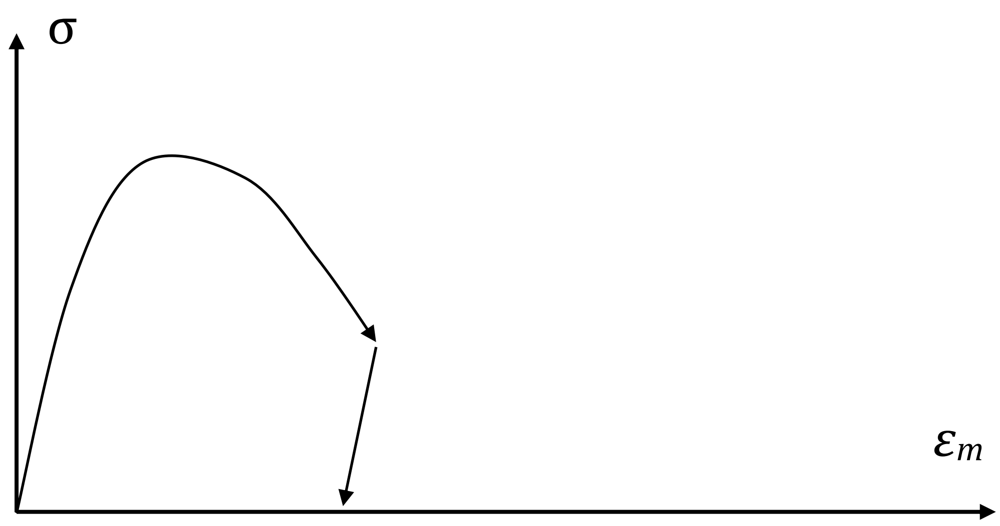


Figure 21 : Plastic behavior in compression

V.2.2. Concrete in tension

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.

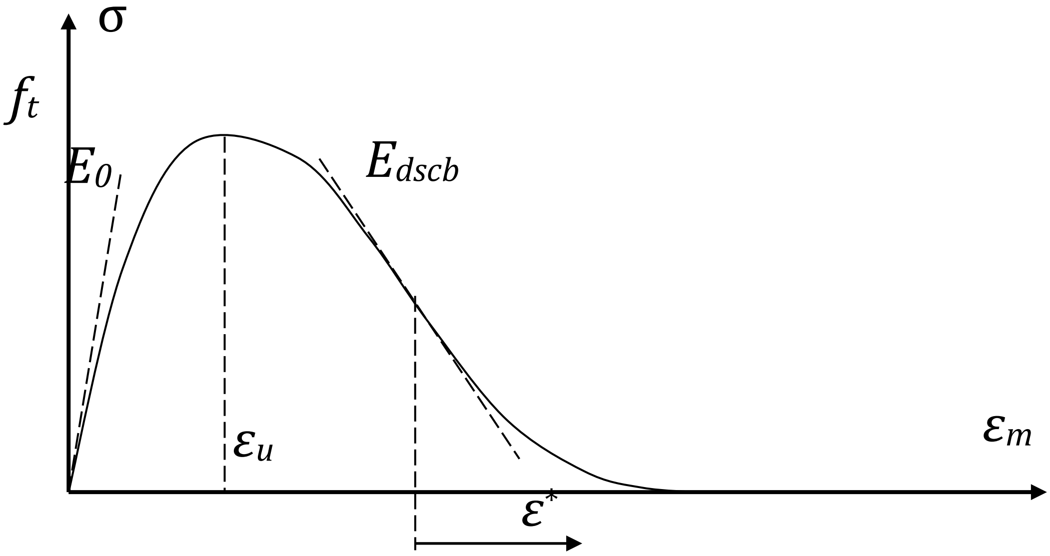


Figure 22 : Stress-strain relationship in tension

The ascending branch is characterized by the tensile strength f_t, and the modulus at the origin E_0. The equation that gives the stress σ and the tangent modulus are, for $\varepsilon_m \leq \varepsilon_u$:

$$\varepsilon_u = 2\frac{f_t}{E_0}$$

$$\sigma = E_0\,\varepsilon_m\left(1-\frac{E_0\,\varepsilon_m}{4\,f_t}\right)$$

$$E_t = E_0\left(1-\frac{E_0\,\varepsilon_m}{2\,f_t}\right)$$

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 compression is the same as the value in compression:

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

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

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

If $\varepsilon^* \le 0$;

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

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

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

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

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

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

$$\sigma = 0$$

$$E_t = 0$$

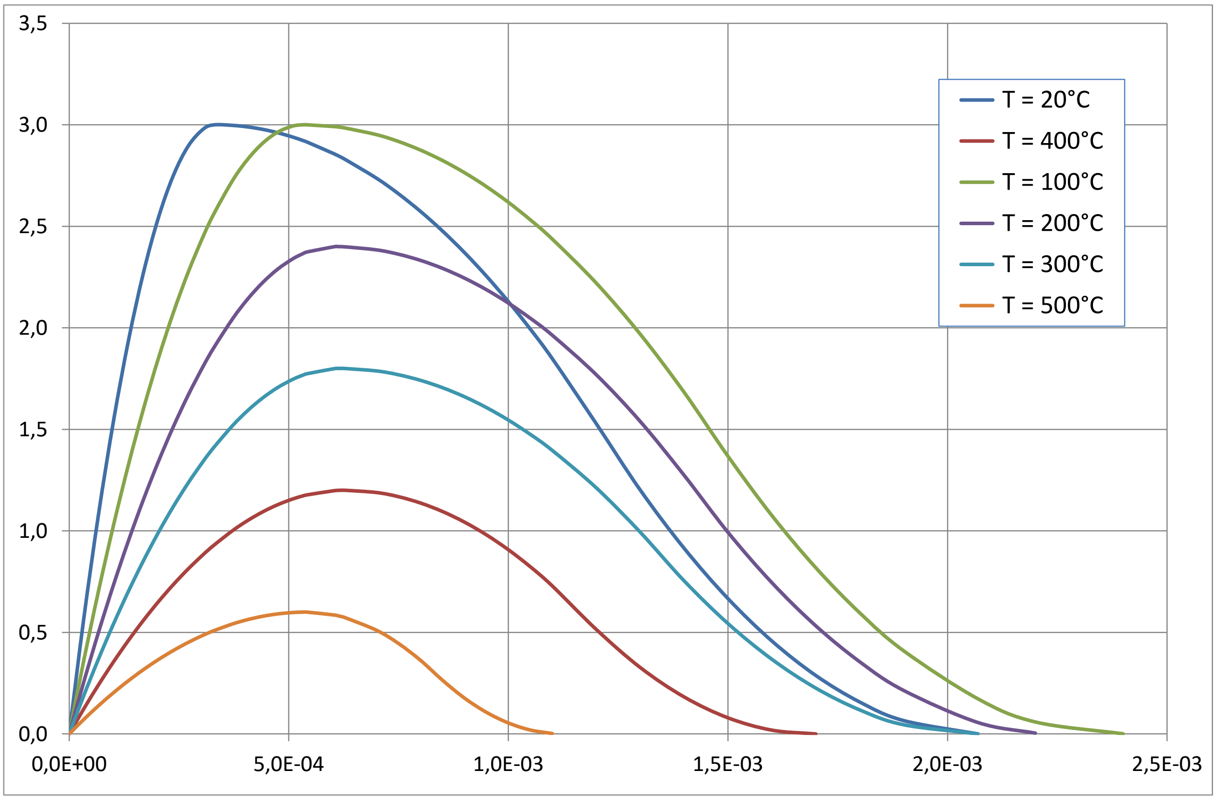


Figure 23 : Stress-strain relationship in tension as a function of the temperature

If concrete has been loaded in tension and, in a later stage, the strain decreases, the unloading is made according to a damage model. 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.

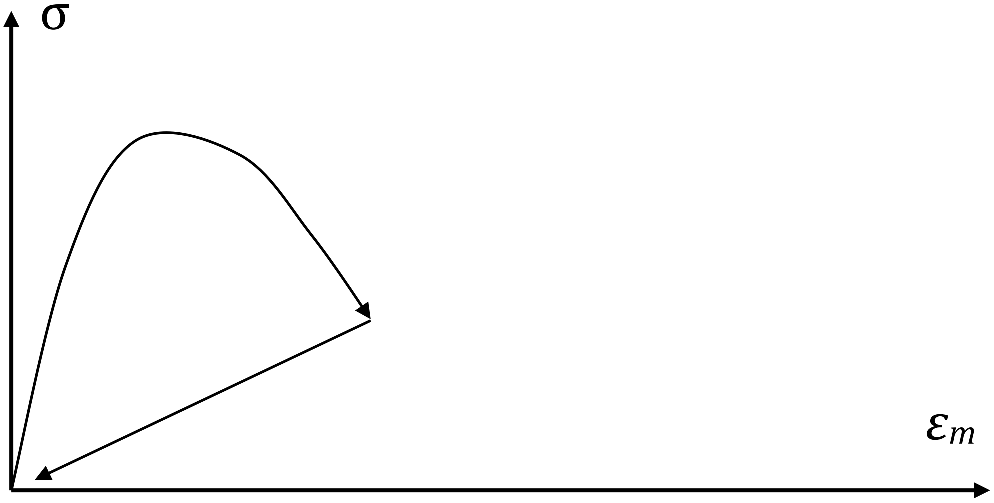


Figure 24 : Damage behavior in tension

Variation of the tensile strength with temperature.

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

$$f_t(T) \quad = \quad k_{ft}(T) \cdot f_t(20)$$

The evolution of $k_{ft}(T)$ with temperature is illustrated in Figure 25, see § 3.2.2.2 in EN 1992-1-2.

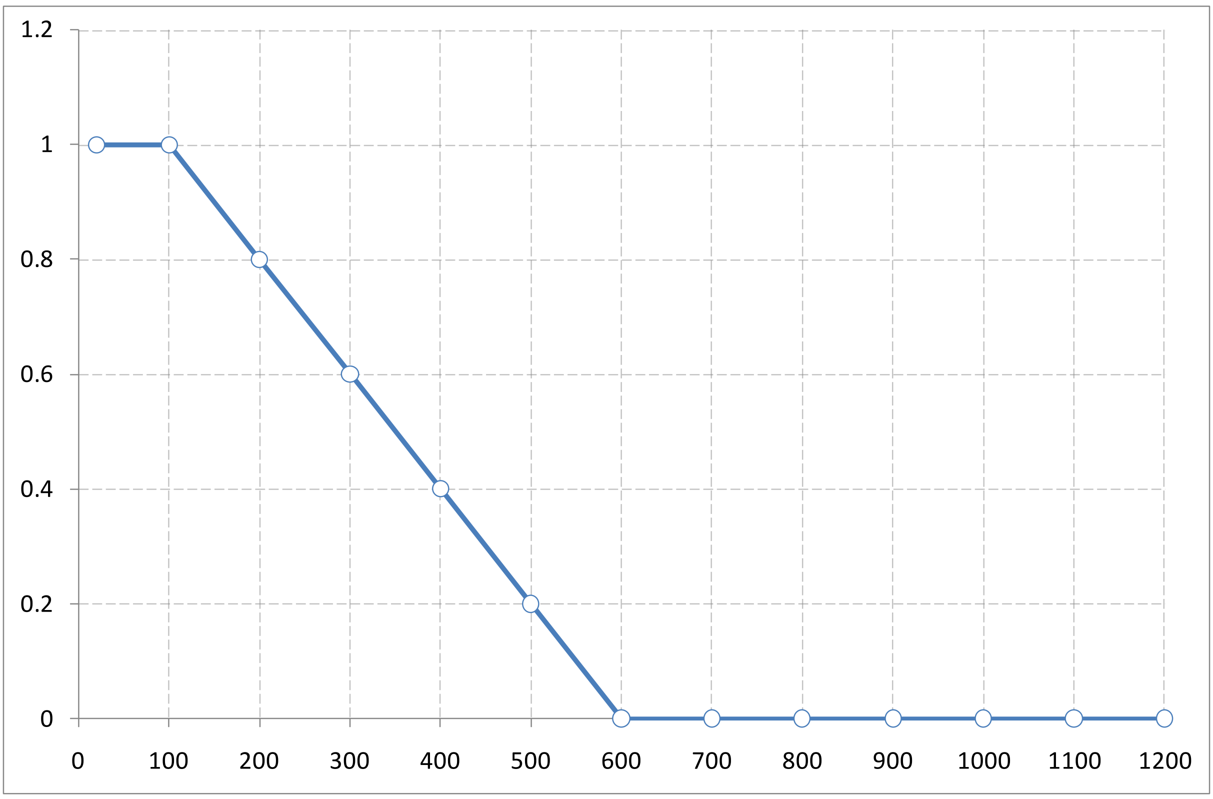


Figure 25 : Tensile strength of concrete

Variation of the modulus at the origin with temperature

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

Figure 26 shows the ascending branch of the stress-strain diagram at different temperatures for concrete with f_c = 30 MPa and f_t = 3 MPa.

If the tensile strength at room temperature is modified (and the compressive strength is unchanged), the curves on the diagram 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 $1/f_c$.

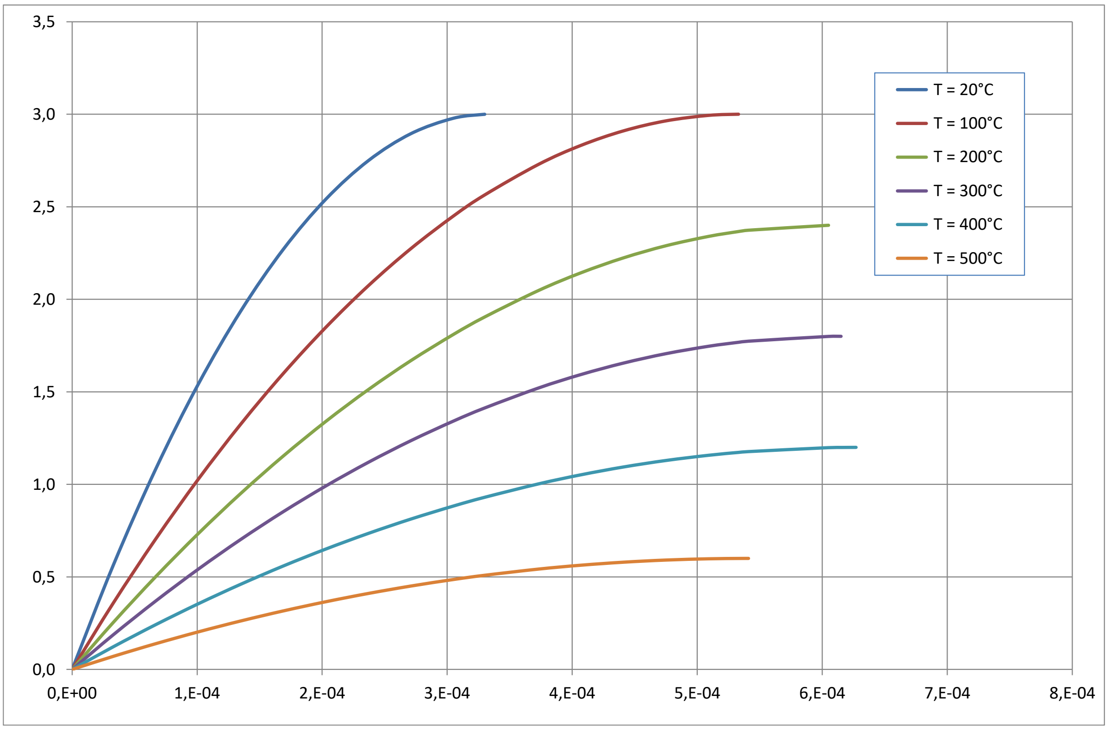


Figure 26: stress-strain diagram in tension (ascending branch)

VI. SILHSC1ETC – CALHSC1ETC, SILHSC2ETC – CALHSC2ETC, SILHSC3ETC – CALHSC3ETC

VI.1. Introduction

This chapter describes the material models SILHSC1ETC, SILHSC2ETC, SILHSC3ETC for siliceous high strength concrete of class 1 to 3 with explicit transient creep strain, and the material models CALHSC1ETC, CALHSC2ETC, CALHSC3ETC for calcareous high strength concrete of class 1 to 3 with explicit transient creep strain. These material models have been developed at University of Liege and implemented in the software SAFIR as uniaxial material models based on the Eurocode 1992-1-2 material properties and the Explicit Transient Creep (ETC) model.

The SAFIR materials SILHSC1ETC, SILHSC2ETC, SILHSC3ETC and CALHSC1ETC, CALHSC2ETC, CALHSC3ETC are based on the Explicit Transient Creep Eurocode constitutive model (ETC) for siliceous and calcareous High Strength Concrete at elevated temperature. The thermal properties are taken from EN1992-1-2. The variation of compressive strength with temperature is taken from table 6.1 of EN1992-1-2 for HSC class 1 to 3.

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 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*, Vol. 48, n°2, pp. 313-329 http://www.springerlink.com/content/3362rp1hv5355462/fulltext.pdf

T. Gernay, J-M Franssen, "A formulation of the Eurocode 2 concrete model at elevated temperature that includes an explicit term for transient creep", *Fire Safety Journal*, 51, pp. 1-9, 2012.
http://hdl.handle.net/2268/114050

Gernay, T., Millard, A., & Franssen, J. M. (2013). A multiaxial constitutive model for concrete in the fire situation: Theoretical formulation. *International Journal of Solids and Structures*, 50(22-23), 3659-3673. https://doi.org/10.1016/j.ijsolstr.2013.07.013

Nomenclature of the models

The user has the choice between:

- Siliceous or calcareous concrete aggregates
- HSC of class 1, 2 or 3

The material models SILHSC1ETC, SILHSC2ETC, SILHSC3ETC refer to siliceous concrete aggregates, whereas the models CALHSC1ETC, CALHSC2ETC, CALHSC3ETC refer to calcareous concrete aggregates. The type of aggregates has an influence on the free thermal strain calculation, according to Part 3.3.1 of EN1992-1-2. It has also an influence on the thermal properties at elevated temperature.

The material models SILHSC1ETC and CALHSC1ETC refer to High Strength Concrete of Class 1, recommended for concrete C55/67 and C60/75.

The material models SILHSC2ETC and CALHSC2ETC refer to High Strength Concrete of Class 2, recommended for concrete C70/85 and C80/95.

The material models SILHSC3ETC and CALHSC3ETC refer to High Strength Concrete of Class 3, recommended for concrete C90/105.

The class of HSC has an influence on the reduction of compressive strength with temperature, according to Table 6.1 of EN1992-1-2.

User input

If CMAT(NM) = SILHSC1ETC, SILHSC2ETC, SILHSC3ETC, CALHSC1ETC, CALHSC2ETC, CALHSC3ETC

3 parameters are required (1 line only)

PARACOLD(2,NM)	Poisson ratio ν	[-]
PARACOLD(3,NM)	Compressive strength f_{ck}	[N/m²]
PARACOLD(4,NM)	Tensile strength f_{tk}	[N/m²]

Input and output of the material subroutines

The input and output material parameters are the same as for the material models SILCON_ETC and CALCON_ETC. Therefore, the user is invited to consult the SAFIR Materials Manual for SILCON_ETC and CALCON_ETC.

VI.2. Description of the material law

The mechanical models for the materials SILHSC1ETC, SILHSC2ETC, SILHSC3ETC, CALHSC1ETC, CALHSC2ETC, CALHSC3ETC are the same as for the material models SILCON_ETC and CALCON_ETC, except that the evolution of the concrete compressive strength if taken from Table 6.1 of EN1992-1-2. Therefore, the user is invited to consult the SAFIR Materials Manual for SILCON_ETC and CALCON_ETC.

VI.2.1. Compressive strength

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

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

The evolution of $k_{fc}(T)$ with temperature for HSC class 1 to 3 is given in Table 4. Table 4 is similar to Table 6.1 of EN1992-1-2.

T [°C]	$f_{c,T}/f_{ck}$		
	Class 1	Class 2	Class 3
20	1.00	1.00	1.00
50	1.00	1.00	1.00
100	0.90	0.75	0.75
200			0.70
250	0.90		
300	0.85		0.65
400	0.75	0.75	0.45
500			0.30
600			0.25
700			
800	0.15	0.15	0.15
900	0.08		0.08
1000	0.04		0.04
1100	0.01		0.01
1200	0.00	0.00	0.00

Table 4 : Reduction of strength at elevated temperature for HSC class 1 to 3

VI.2.2. Transient creep strain

The transient creep strain calculation is made in accordance with the Explicit Transient Creep model presented in the SAFIR Materials Manual for SILCON_ETC and CALCON_ETC and in the references listed above. The main steps of this calculation are reminded here below.

Transient creep strain is computed incrementally. 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:

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

The ratio f_c / f_{ck} is not the same for Normal strength Concrete (NC) as for High Strength Concrete (HSC) since for HSC, the reduction of strength at elevated temperature is given by Table 6.1 of EN1992-1-2. As a consequence, the function $\phi(T)$ is different for the material models implemented for NC (SILCON_ETC and CALCON_ETC) and the material models implemented for HSC (SILHSCxETC and CALHSCxETC). The values of function $\phi(T)$ are given in Table 5 for NC and HSC class 1 to 3.

T [°C]	Φ				
	NC sil	NC cal	HSC1	HSC2	HSC3
20	0.0000	0.0000	0.0000	0.0000	0.0000
100	0.0010	0.0010	0.0011	0.0013	0.0013
200	0.0018	0.0017	0.0019	0.0022	0.0024
300	0.0024	0.0022	0.0024	0.0027	0.0031
400	0.0049	0.0043	0.0049	0.0049	0.0081
500	0.0106	0.0086	0.0106	0.0106	0.0211
600	0.0274	0.0206	0.0274	0.0274	0.0493
700	0.0389	0.0271	0.0389	0.0389	0.0583
800	0.0733	0.0407	0.0733	0.0733	0.0733
900	0.1250	0.0667	0.1250	0.1250	0.1250
1000	0.2500	0.1667	0.2500	0.2500	0.2500
1100	1.0000	0.5000	1.0000	1.0000	1.0000

Table 5 : Function $\phi(T)$ for different types of concrete

VI.3. Transient creep strain of high strength concrete

The transient creep strain for the material models SILHSC1ETC and SILHSC3ETC are plotted on Figure 27 and Figure 28 for stress levels of 0.20, 0.30 and 0.40.

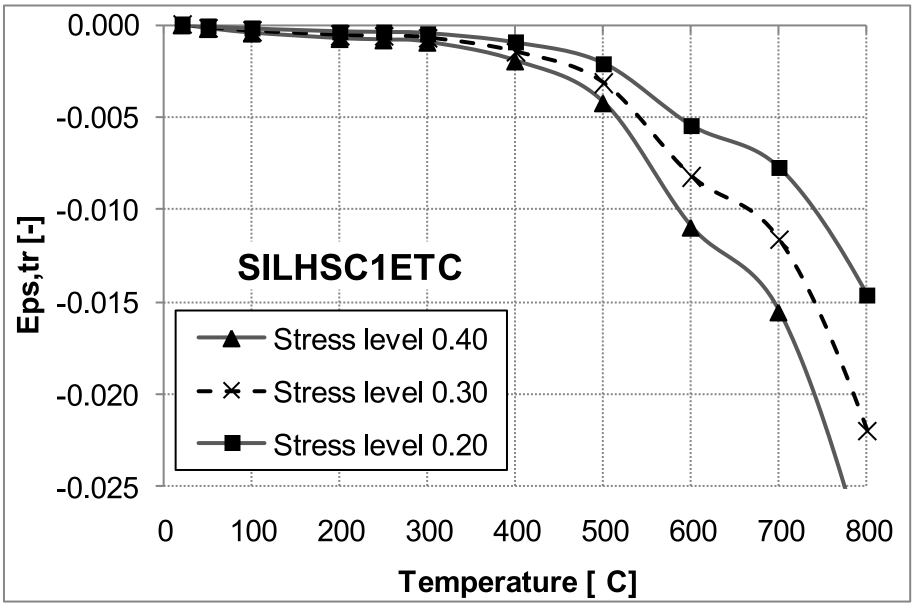


Figure 27 : Transient creep strain for HSC of class 1

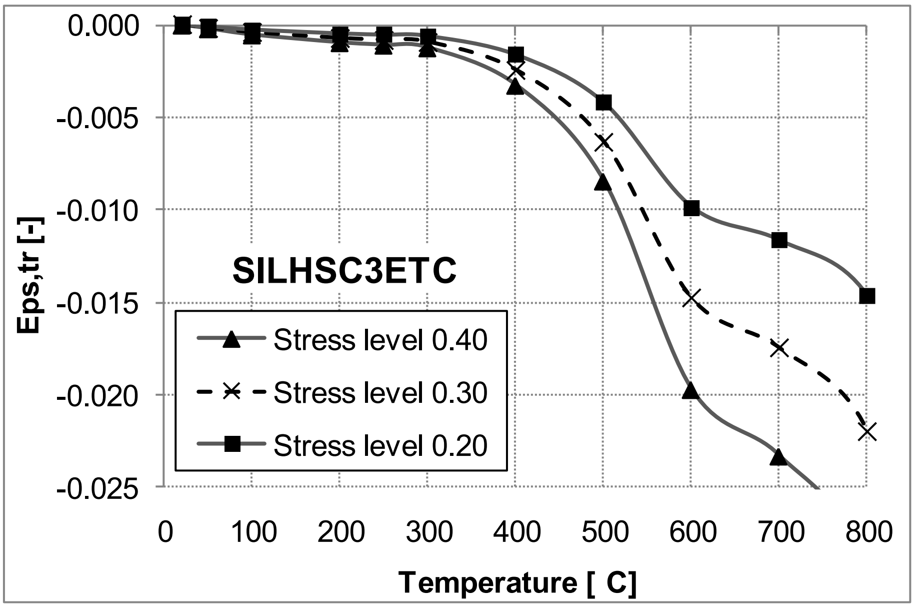


Figure 28 : Transient creep strain for HSC of class 3

In a recent paper, Bo Wu et al. have proposed fitting equations for the transient creep strain of HSC with PP fibers, based on experimental data [Bo Wu et al., “Creep Behavior of High-Strength Concrete with Polypropylene Fibers at Elevated Temperatures”, ACI Materials Journal, V. 107, No. 2, 2010]. Figure 29 compares the transient creep strains obtained from HSC with PP fibers (model by Bo Wu et al.) and HSC without PP fibers (model by Hu and Dong, 2002, cited in Bo Wu et al.) with the transient creep strains computed by the SAFIR material models for HSC of class 1 and class 3. The stress level considered in Figure 29 is 0.4.

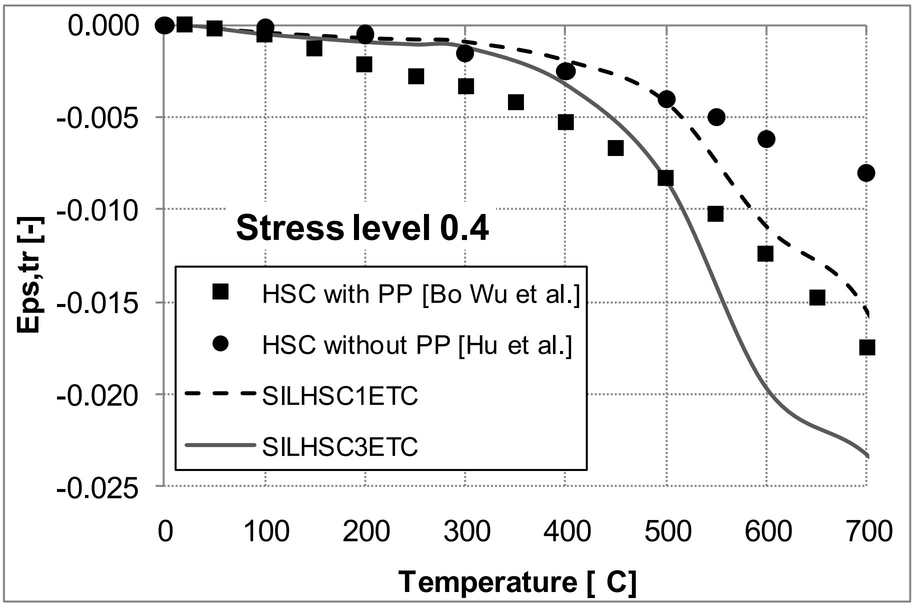


Figure 29 : Comparison of different models of transient creep strain for HSC

VII. SILHSC1_EN – CALHSC1_EN, SILHSC2_EN – CALHSC2_EN, SILHSC3_EN – CALHSC3_EN

VII.1. Introduction

This chapter describes the material models SILHSC1_EN, SILHSC2_EN, SILHSC3_EN for siliceous high strength concrete of class 1 to 3 according to the model of EN 1992-1-2, and the material models CALHSC1_EN, CALHSC2_EN, CALHSC3_EN for calcareous high strength concrete of class 1 to 3 according to the model of EN 1992-1-2. These material models have been developed at University of Liege and implemented in the software SAFIR as uniaxial material models based on the Eurocode 1992-1-2 material properties.

The SAFIR materials SILHSC1_EN, SILHSC2_EN, SILHSC3_EN and CALHSC1_EN, CALHSC2_EN, CALHSC3_EN are the material models from Eurocode EN 1992-1-2 for siliceous and calcareous High Strength Concrete at elevated temperature.

The variation of compressive strength with temperature is taken from table 6.1 of EN1992-1-2 for HSC class 1 to 3.

<u>*Nomenclature of the models*</u>

The user has the choice between:

- Siliceous or calcareous concrete aggregates
- HSC of class 1, 2 or 3

The material models SILHSC1_EN, SILHSC2_EN, SILHSC3_EN refer to siliceous concrete aggregates, whereas the models CALHSC1_EN, CALHSC2_EN, CALHSC3_EN refer to calcareous concrete aggregates. The type of aggregates has an influence on the free thermal strain calculation, according to Part 3.3.1 of EN1992-1-2. It has also an influence on the thermal properties at elevated temperature.

The material models SILHSC1_EN and CALHSC1_EN refer to High Strength Concrete of Class 1, recommended for concrete C55/67 and C60/75.

The material models SILHSC2_EN and CALHSC2_EN refer to High Strength Concrete of Class 2, recommended for concrete C70/85 and C80/95.

The material models SILHSC3_EN and CALHSC3_EN refer to High Strength Concrete of Class 3, recommended for concrete C90/105.

The class of HSC has an influence on the reduction of compressive strength with temperature, according to Table 6.1 of EN1992-1-2.

User input

If CMAT(NM) = SILHSC1_EN, SILHSC2_EN, SILHSC3_EN, CALHSC1_EN, CALHSC2_EN, CALHSC3_EN

3 parameters are required (1 line only)

PARACOLD(2,NM)	Poisson ratio ν	[-]
PARACOLD(3,NM)	Compressive strength f_{ck}	[N/m²]
PARACOLD(4,NM)	Tensile strength f_{tk}	[N/m²]

VII.2. Compressive strength

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

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

The evolution of $k_{fc}\left(T\right)$ with temperature for HSC class 1 to 3 is given in *Table 6*.

Table 6 is similar to Table 6.1 of EN1992-1-2.

T [°C]	$f_{c,T}/f_{ck}$		
	Class 1	Class 2	Class 3
20	1.00	1.00	1.00
50	1.00	1.00	1.00
100	0.90	0.75	0.75
200			0.70
250	0.90		
300	0.85		0.65
400	0.75	0.75	0.45
500			0.30
600			0.25
700			
800	0.15	0.15	0.15
900	0.08		0.08
1000	0.04		0.04
1100	0.01		0.01
1200	0.00	0.00	0.00

Table 6 : Reduction of strength at elevated temperature for HSC class 1 to 3

VIII. USER MATERIALS FOR STRUCTURAL ANALYSIS

VIII.1. USER_ELAS

If CMAT = USER_ELAS

paracold(1,NM)	Young's modulus at 20°C.
paracold(2,NM)	Poisson's ratio at 20°C.
paracold(3,NM)	Compressive strength at 20°C.
paracold(4,NM)	Tensile strength at 20°C.

This USER_ELAS material is a linear elastic - brittle material, with no thermal strain. Its behavior is linear elastic up to the defined strength and then reduces to zero. The strength and modulus can be different in tension and compression.

USER_ELAS allows the user to define their own reduction factors. USER_ELAS will behave at elevated temperatures according to the reduction factors specified in the file "*USER_ELAS.TXT*" that the user has to create and locate in the same folder as the input file. In the file "*USER_ELAS.TXT*" four factors are given at different temperatures: $k_{E,c}$, $k_{E,t}$, k_{fc}, k_{ft}. Between two given temperatures, a linear interpolation is performed by SAFIR. $k_{E,c}$, $k_{E,t}$, k_{fc}, k_{ft} are the reduction factors at elevated temperatures relative to the values of the modulus E in compression, the modulus E in tension, the compressive strength, and the tensile strength at 20°C.

Structure of the file "*USER_ELAS.TXT*"

One line

`Number_of_T:`, *number_of_T*

- `Number_of_T`

  Command.

- *number_of_T*

  Quantity of elevated temperatures at which the values of the reduction factors are given.

One line

```
T        KEc        KEt        Kfc        Kft
```

One line for each temperature added to series, *number_of_T* lines

T, $k_{Ec}(T)$, $k_{Et}(T)$, $k_{fc}(T)$, $k_{ft}(T)$

- T Temperature at which the reduction factors are given.
- $k_{Ec}(T)$ Reduction factor relative to the value of E (Young's modulus) in compression at 20°C.
- $k_{Et}(T)$ Reduction factor relative to the value of E (Young's modulus) in tension at 20°C.
- $k_{fc}(T)$ Reduction factor relative to the value of compressive strength at 20°C.
- $k_{ft}(T)$ Reduction factor relative to the value of tensile strength at 20°C.

VIII.2. USER_STEEL

If CMAT = USER_STEEL

paracold(1,NM)	Young's modulus at 20°C.
paracold(2,NM)	Poisson's ratio at 20°C.
paracold(3,NM)	Yield strength at 20°C.
paracold(4,NM)	critical temperature (in °C) beyond which the yield strength is not fully recovered during cooling.
paracold(5,NM)	the rate of decrease of the residual yield strength if the temperature has exceeded the critical temperature.

This USER_STEEL material has the same expression of stress-strain relationship as steel of Eurocodes but it will behave at elevated temperatures according to the decreasing curves specified in the file "*USER_STEEL.TXT*" that the user has to create and locate in the same folder as the input file.

In the file "*USER_STEEL.TXT*", k_E, k_{fy}, k_{fp}, ε_{th}, ε_y, ε_t and ε_u are given at different temperatures. Between two temperatures, a linear interpolation is performed by SAFIR.

Structure of the file "*USER_STEEL.TXT*"

One line

`Number_of_T:`, *number_of_T*

- `Number_of_T`

  Command.

- *number_of_T*

  Quantity of elevated temperatures at which the values of the reduction factors are given.

One line

```
T   KE   Kfy   Kfp     EPSth      EPSy      EPSt      EPSu
```

One line for each temperature added to series, *number_of_T* lines

T, $k_E(T)$, $k_{fy}(T)$, $k_{fp}(T)$, $\varepsilon_{th}(T)$, $\varepsilon_y(T)$, $\varepsilon_t(T)$, $\varepsilon_u(T)$

- T Temperature at which the reduction factors are given.
- $k_E(T)$ Reduction factor relative to the value of E (Young's modulus) at 20°C.
- $k_{fy}(T)$ Reduction factor relative to the value of fy (effective yield strength) at 20°C.
- $k_{fp}(T)$ Reduction factor relative to the value of fp (limit of proportionality) at 20°C.
- $\varepsilon_{th}(T)$ Thermal elongation at temperature T.
- $\varepsilon_y(T)$ Yield strain at temperature T.
- $\varepsilon_t(T)$ Limiting strain for yield strength at temperature T.
- $\varepsilon_u(T)$ Ultimate strain at temperature T.

VIII.3. USER_STL2D

USER_STL2D is a plane stress material law for steel for which users can specify the evolution of the properties with temperature. It is to be used with shell finite elements.

This USER_STL2D material has the same expression of stress-strain relationship as STEELEC32D but it will behave at elevated temperatures according to the decreasing curves specified in the file “USER_STEEL.TXT” that the user has to create and locate in the same folder as the input file.

The structure of “USER_STEEL.TXT” is the same as described for the material USER_STEEL. The reader is referred to USER_STEEL for more information.

VIII.4. USER_CONC

The material `USER_CONC` is is a uniaxial concrete material which behavior can be defined by the user. It requires a file "*USER_CONC.TXT*" that the user must create and locate in the same folder as the input file.

If `CMAT = USER_CONC`

paracold(2,NM)	Poisson ratio.
paracold(3,NM)	Compressive strength.

The behavior in compression is based on the generalized expression of stress-strain relationship from Eurocode 1992-1-2, as given below:

Range	Stress $\sigma(\theta)$
$\varepsilon \leq \varepsilon_{c1,\theta}$	$\dfrac{n\ \varepsilon_m\ f_{c,\theta}}{\varepsilon_{c1,\theta}\left[(n-1)+\left(\frac{\varepsilon_m}{\varepsilon_{c1,\theta}}\right)^n\right]}$
$\varepsilon_{c1,\theta} < \varepsilon \leq \varepsilon_{cu1,\theta}$	Nonlinear descending branch

In the file "*USER_CONC.TXT*", k_{fc}, $\varepsilon_{c1,\theta}$, $\varepsilon_{cu1,\theta}$, n and $\varepsilon_{th,\theta}$ are given at different temperatures. Between two temperatures, a linear interpolation is performed on these values by SAFIR.

k_{fc} is the reduction factor at elevated temperature relative to the value $f_{c,\theta}$. n is the exponent of the stress-strain law in compression as shown in the equation above.

The Young modulus derives from the parameters of the stress-strain law. It is given by:

$$E = \frac{n\ f_{c,\theta}}{(n-1)\ \varepsilon_{c1,\theta}}$$

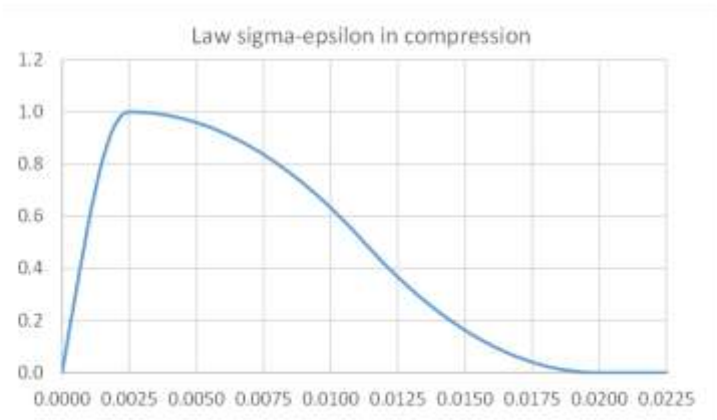


Figure 6: Law sigma-epsilon in compression (shown as positive)

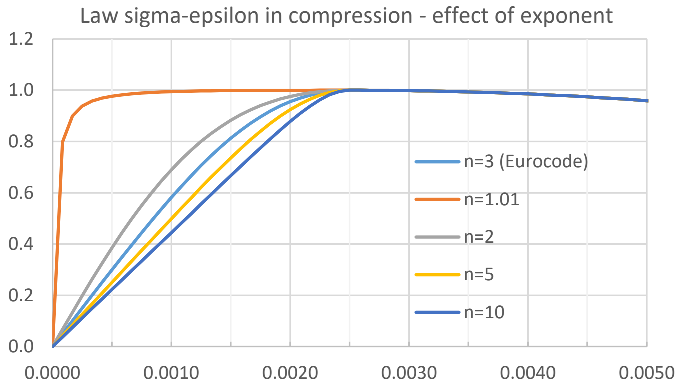


Figure 7: Law sigma-epsilon in compression (shown as positive) - Effect of exponent

Unloading in compression is performed based on a plasticity model.

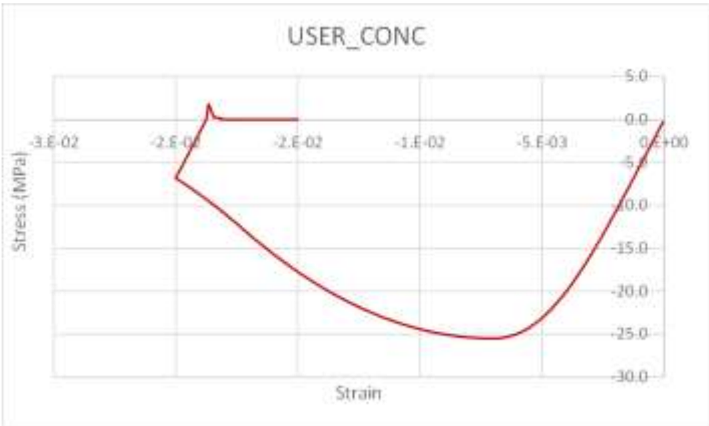


Figure 8: Unloading in compression

The behavior in tension follows a multi-linear behavior according to the points specified in the file "*USER_CONC.TXT*". In this file, a quantity of couples (ε, σ) are given at different temperatures for the behavior in tension. The user can decide on the quantity of couples (ε, σ), as well as on the quantity of temperatures. Between two defined (ε, σ), the behavior is linear.

At a given temperature,
ε_1, σ_1 define the first point in the constitutive stress-strain law of concrete in tension.
ε_2, σ_2 defines the second point. Between the points (ε_1, σ_1) and (ε_2, σ_2), the behavior is linear.

The user defines as many points as desired.

Notes :

1) the law is assumed to start at (0,0). Therefore, the point (0,0) (origin of the stress-strain law) should not be defined in the "*USER_CONC.TXT*" file.
2) The points have to be defined in ascending order of strain ε (meaning that $\varepsilon_{i+1} > \varepsilon_i$).
3) For any strain larger than the last defined strain, the stress is set to zero.
4) Between two temperatures, a linear interpolation is performed by SAFIR.
5) the SAFIR computation will stop if a temperature in any point in the material exceeds the highest defined temperature in "*USER_CONC.TXT*".
6) Units follow the convention of the software (material strength in Pascal).

Unloading in tension is performed based on a damage model.

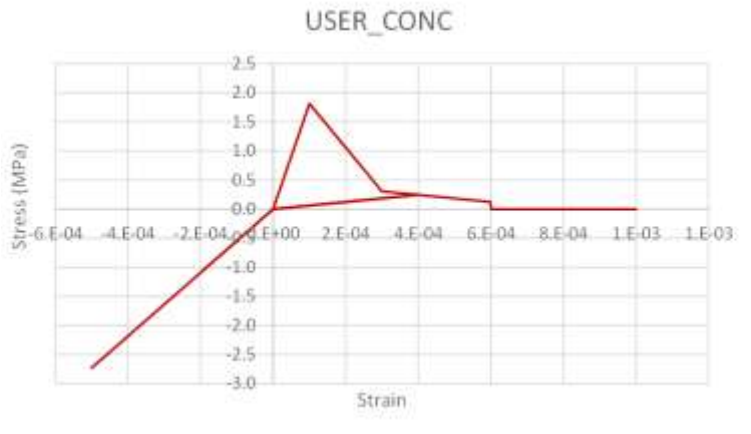


Figure 9: Unloading in tension

<u>In cooling</u>, both in compression and in tension, the behavior is irreversible when the temperature cools down. In other words, the parameters of the stress-strain laws are evaluated based on the maximum temperature reached in the integration point over the history of the fire, and not on the current temperature.

An example of USER_CONC.TXT file is provided below.

Structure of the file "*USER_CONC.TXT*"

One line

`Number_of_T:`, *number_of_T*

- `Number_of_T:`

    Command.

- *number_of_T*

    Quantity of elevated temperatures at which the values of the points defining the stress-strain law in compression are given.

One line

`T        kfc      EPSC1     EPSCU1          n      EPSth`

One line for each temperature added to series, *number_of_T* lines

T, $k_{fc}(T)$, $\varepsilon_{c1}(T)$, $\varepsilon_{cu1}(T)$, $n(T)$

- T Temperature at which the parameters are given.
- $k_{fc}(T)$ Reduction factor relative to the value of f_c (compressive strength) at 20°C.
- $\varepsilon_{c1}(T)$ Strain at peak stress at temperature T.
- $\varepsilon_{cu1}(T)$ Ultimate compression strain at temperature T.
- n Exponent of compression stress-strain law at temperature T.
- $\varepsilon_{th}(T)$ Thermal elongation at temperature T.

One line

`Number_of_T:`, *number_of_T*

- `Number_of_T:`

    Command.

- *number_of_T*

    Quantity of elevated temperatures at which the values of the points defining the stress-strain law in tension are given.

One line

`Number_of_EPS:`, *number_of_eps*

- `Number_of_eps:`

  Command.

- *number_of_eps*

  Quantity m of strains at which the values of the stress are given (i.e. quantity of points in the stress-strain law in tension which are specified at a given temperature).

One line

`T EPS1 SIG1 EPS2 SIG2 … EPSm SIGm`

One line for each temperature added to series, *number_of_T* lines

$T, \varepsilon_1(T), \sigma_1(T), \varepsilon_2(T), \sigma_2(T), \varepsilon_3(T), \sigma_3(T), \ldots, \varepsilon_m(T), \sigma_m(T)$

- T Temperature at which the tensile stress-strain law is defined.
- $\varepsilon_1(T)$ First defined strain at the temperature T.
- $\sigma_1(T)$ First defined stress at the temperature T (i.e. the one corresponding to ε_1(T)).

…

- $\varepsilon_m(T)$ Last defined strain at the temperature T.
- $\sigma_m(T)$ Last defined stress at the temperature T (i.e. the one corresponding to ε_m(T)).

Example, the following file describes a material that has a behaviour in compression according to the Eurocode 2 part 1-2 for siliceous aggregates concrete. The material has a behaviour in tension defined by 3 points in the stress-strain space (plus the origin 0,0). The behaviour at 200°C is plotted on the graph below (Figure 10).

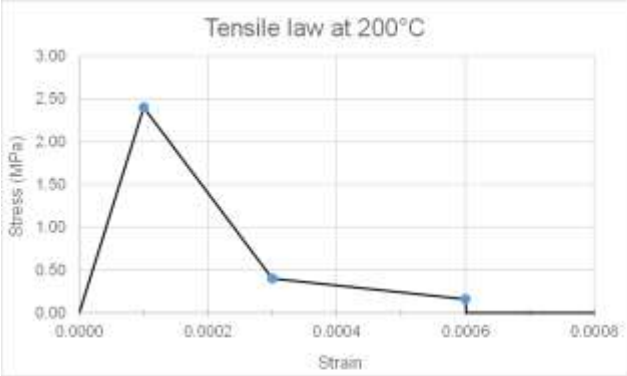


Figure 10: Tensile law at 200°C.

```
Number_of_T: 14
         T       kfc     EPSC1     EPSCU1         n     EPSth
        0.     1.000    0.0025    0.0200          3    0.0000
       20.     1.000    0.0025    0.0200          3    0.0000
      100.     1.000    0.0040    0.0225          3    0.0007
      200.     0.950    0.0055    0.0250          3    0.0018
      300.     0.850    0.0070    0.0275          3    0.0031
      400.     0.750    0.0100    0.0300          3    0.0049
      500.     0.600    0.0150    0.0325          3    0.0072
      600.     0.450    0.0250    0.0350          3    0.0102
      700.     0.300    0.0250    0.0375          3    0.0140
      800.     0.150    0.0250    0.0400          3    0.0140
      900.     0.080    0.0250    0.0425          3    0.0140
     1000.     0.040    0.0250    0.0450          3    0.0140
     1100.     0.010    0.0250    0.0475          3    0.0140
     1200.     0.000    0.0250    0.0475          3    0.0140
Number_of_T: 4
Number_of_EPS: 3
         T      EPS1      SIG1      EPS2      SIG2      EPS3      SIG3
        0.    0.0001    3.00e6   0.0003    0.50e6    0.0006    0.20e6
      200.    0.0001    2.40e6   0.0003    0.40e6    0.0006    0.16e6
      600.    0.0001    0.05e6   0.0003    0.02e6    0.0006    0.01e6
     1200.    0.0001    0.05e6   0.0003    0.02e6    0.0006    0.01e6
```

Page voluntarily left blank

IX. REFERENCES

Cooper, L.Y. (1997), *The thermal response of gypsum-panel/steel-stud wall systems exposed to fire environments - a simulation for use in zone-type fire models*, NISTIR 6027, National Institute of Standards and Technology, Gaithersburg MD.

EN 1991-1-2 (2002), *Eurocode 1: actions on structures – Part 1–2: general actions – actions on structures exposed to fire*, CEN, Brussels.

EN 1992-1-2 (2005), *Eurocode 2: design of concrete structures – Part 1–2: general rules – structural fire design*, CEN, Brussels.

EN 1993-1-2 (2005), *Eurocode 3: design of steel structures – Part 1–2: general rules – structural fire design*, CEN, Brussels.

EN 1994-1-2 (2005), *Eurocode 4: design of composite steel and concrete structures. Part 1–2: general rules – structural fire design*, CEN, Brussels.

EN 1995-1-2 (2004), *Eurocode 5: design of timber structures – Part 1–2: general – structural fire design*, CEN, Brussels.

EN 1999-1-2 (2007), *Eurocode 9: design of aluminum structures – Part 1–2: structural fire design*, CEN, Brussels.

Franssen, J.M. (1993), *Thermal elongation of concrete during heating up to 700 °C and cooling*, University of Liege. <http://hdl.handle.net/2268/531>.

Franssen, J.M., Cowez, B. Gernay, T. (2014), "Effective stress method to be used in beam finite elements to take local instabilities into account", *Fire Safety Science 11*, 544-557.

Franssen, J. M., Gernay, T. (2017). Modeling structures in fire with SAFIR®: Theoretical background and capabilities. *Journal of Structural Fire Engineering*, 8(3), 300-323.

Gernay, T. Franssen, J.M. (2012), "A formulation of the Eurocode 2 concrete model at elevated temperature that includes an explicit term for transient creep", *Fire Safety Journal* 51, 1–9.

Gernay, T. (2012), "Effect of transient creep strain model on the behavior of concrete columns subjected to heating and cooling", *Fire Technology* 48(2), 313–29.

Gernay, T., Millard, A. Franssen, J.M. (2013), "A multiaxial constitutive model for concrete in the fire situation: Theoretical formulation", *Int J Solids Struct* 50(22-23), 3659-3673.

Gernay, T. Franssen, J.M. (2015), "A plastic-damage model for concrete in fire: Applications in structural fire engineering", *Fire Safety Journal* 71, 268–278.

Khorasani, N. E., Gardoni, P., Garlock, M. (2015). Probabilistic fire analysis: material models and evaluation of steel structural members. *Journal of Structural Engineering*, 141(12), 04015050.

Qureshi, R., Ni, S., Elhami Khorasani, N., Van Coile, R., Hopkin, D., Gernay, T. (2020). Probabilistic models for temperature-dependent strength of steel and concrete. *Journal of Structural Engineering*, 146(6), 04020102.

Ni, S., Gernay, T. (2021). Considerations on computational modeling of concrete structures in fire. *Fire Safety Journal*, 120, 103065.