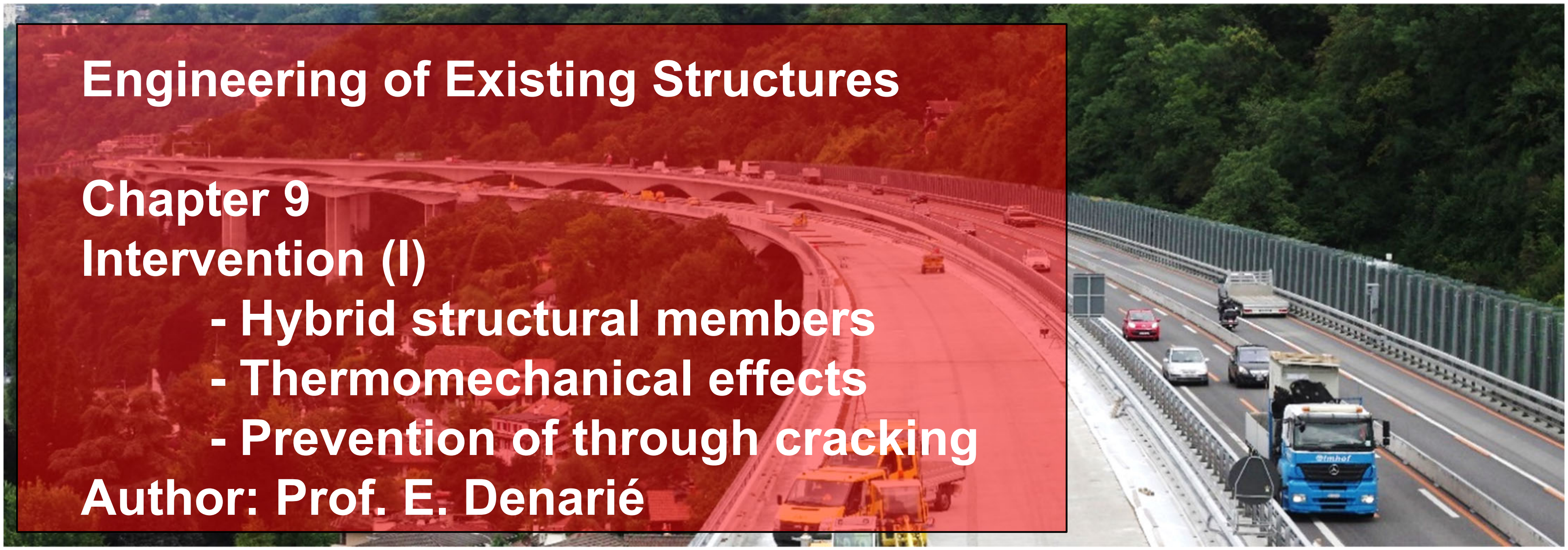
Engineering of Existing Structures - CIVIL-511
Civil Engineering - Master 1 and 3
Teachers: Prof. Emmanuel Denarié, Prof. Alain Nussbaumer



Engineering of Existing Structures

Chapter 9
Intervention (I)
- Hybrid structural members
- Thermomechanical effects
- Prevention of through cracking

Author: Prof. E. Denarié

ENAC IIC **CONSTRUCT/RESSLAB**

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1. Introduction

Interventions – 4 chapters

Chapter 9: hybrid concrete members – new on old concretes

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Chapter 12: strengthening (II): glued CFRP lamellas

➔ Gives bases of possible intervention techniques to be proposed in intervention recommendations

➔ Address causes of deterioration phenomena and lacks in structural safety and serviceability

- Composite structures formed of materials of different kinds and ages are very common.
- Slabs on grade, steel-concrete, wood-concrete, concrete-concrete, concrete repairs, cement-based overlays, etc.
- Do these different kinds of practical applications have a common background ?
- Can they be treated by a common theoretical approach ?
- What are the benefits of such an approach ?

Actions

Actions = imposed forces or displacements,

Imposed (differential) deformations or displacements

- deformations due to autogenous effects,
- deformations due to drying shrinkage,
- deformations due to thermo-mechanical effects associated to hydration of binders (temperature gradients), at early age,
- deformations due to thermo-mechanical effects-temperature gradients, at long term,
- settlements,

Imposed forces

- braking forces of vehicles,
- moving (fatigue) or still loads – permanent loads in storage facilities,
- seismic loads,
- etc.

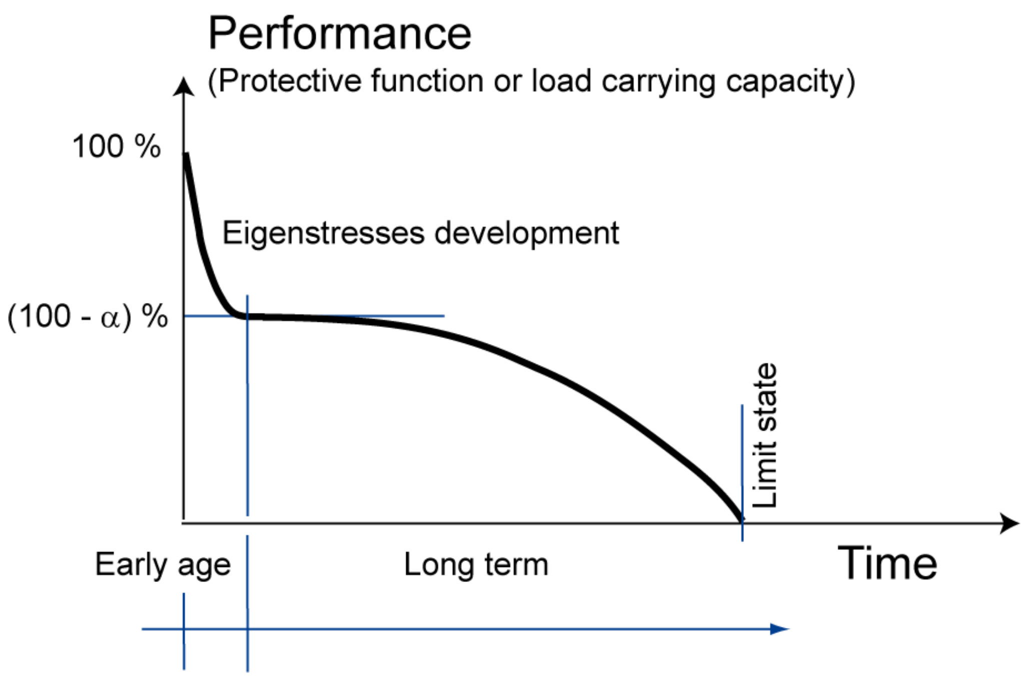
Forms of restraint , effect of joints

Restraint = all mechanical effects that counteract the deformations of a given body.

- Frictional forces on the subgrade of slabs on grade.
- Dowels and connectors in steel-concrete composite beams.
- Reinforcement bars, formworks.
- Static system.
- Joints (artificial or cracks) = local release of the restraint, with varying consequences on the overall behaviour, positive or negative.

Combination of restraints and joints defines the *kinematic system of the structure*.

Performance of composite (hybrid) structures



Bernard (2000) [1]

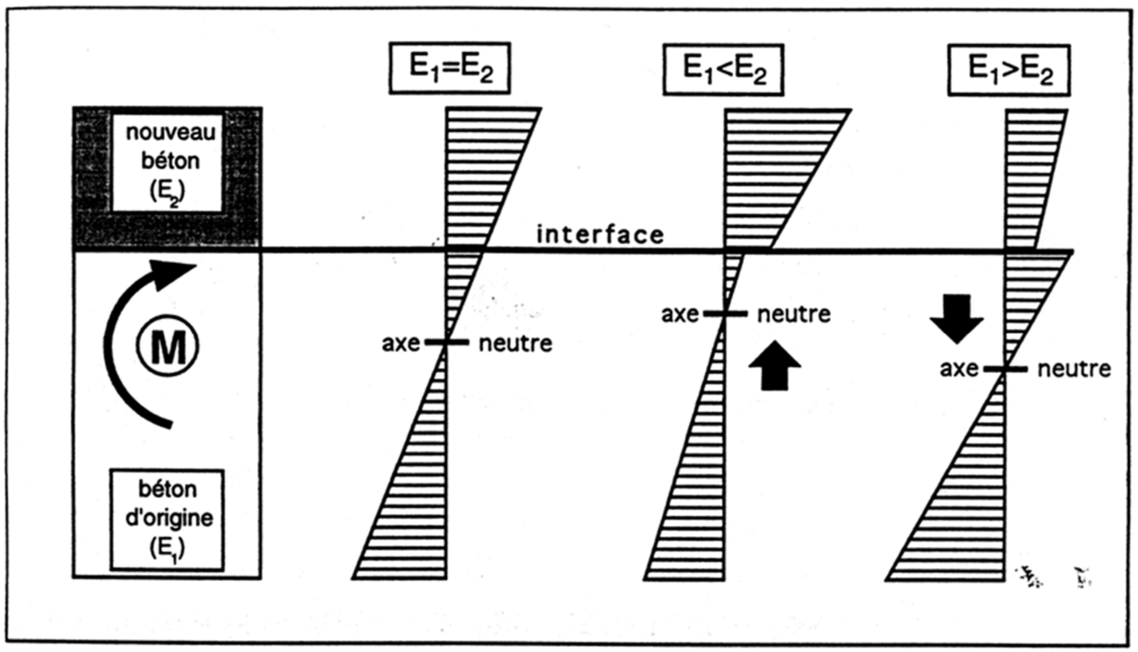
Required performances

- protective function of the new layer and its serviceability.

- load-bearing capacity of the hybrid component and its behavior at serviceability and ultimate (limit) state.

➔ Initial loss of performance due to development of eigenstresses at early age

2. Mechanical response of hybrid structures



Influence of the relative stiffness of new concrete/old concrete on the distribution of normal bending stresses, according to Bissonnette (1996) [2]

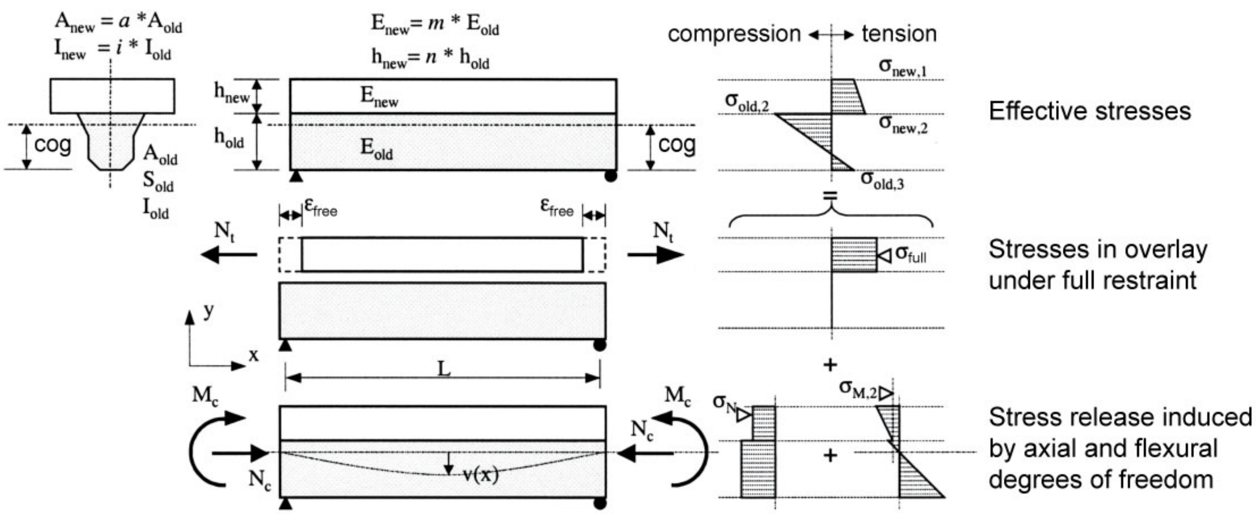
Stresses

Silfwerbrand (1997) [3]

Stress = material stiffness × free strain × degree of restraint

Stiffness: f(E_{mod}, creep/relaxation) ➔ material property,
Free strain: ➔ material property

Degree of restraint: ➔ structural property



Adapted form Bernard (2000) [1]

Hypotheses:

- linear-elastic materials
- perfect bond between layers
- Poisson ratios = 0
- Bernouilly applies
- ε_{free} = uniform,
in new layer only

➔ Prestressing analogy

Degree of restraint

Silfwerbrand (1997) [3], Bernard (2000) [1], Denarié (2004) [4]

$$\mu = \frac{\sigma_{new,2}}{\sigma_{full}} = \frac{\sigma_{full} - \sigma_N - \sigma_{M,2}}{\sigma_{full}} = 1 - \mu_N - \mu_M$$

μ_N: release associated to axial degree of freedom of hybrid system

μ_M: release associated to flexural degree of freedom of hybrid system

$\sigma_{new,2}$: tensile stress at interface level, in new layer

σ_{full}: tensile stress at interface level, in new layer for full restraint

$$\mu_N = \frac{\sigma_N}{\sigma_{full}} = \frac{ma}{ma+1} = \frac{1}{1+1/ma} = \frac{1}{1+\dfrac{E_{old}.A_{old}}{E_{new}.A_{new}}}$$

$$n = \frac{h_{new}}{h_{old}}$$

$$m = \frac{E_{new}}{E_{old}}$$

$$\mu_M = \frac{\sigma_{M,2}}{\sigma_{full}} = \frac{N_t(cog_{new} - cog)}{W_2}\frac{1}{E_{new}.\varepsilon_{free.}}$$

$$= \frac{A_{new} \cdot (cog_{new} - cog) \cdot [m \cdot (h_{old} - cog)]}{[I_{old} + A_{old}(cog - cog_{old})^2 + m \cdot (I_{new} + A_{new}(cog_{new} - cog)^2)]}$$

$$a = \frac{A_{new}}{A_{old}}$$

$$cog = \frac{S_{old} + m \cdot S_{new}}{A_{old} + m \cdot A_{new}}$$

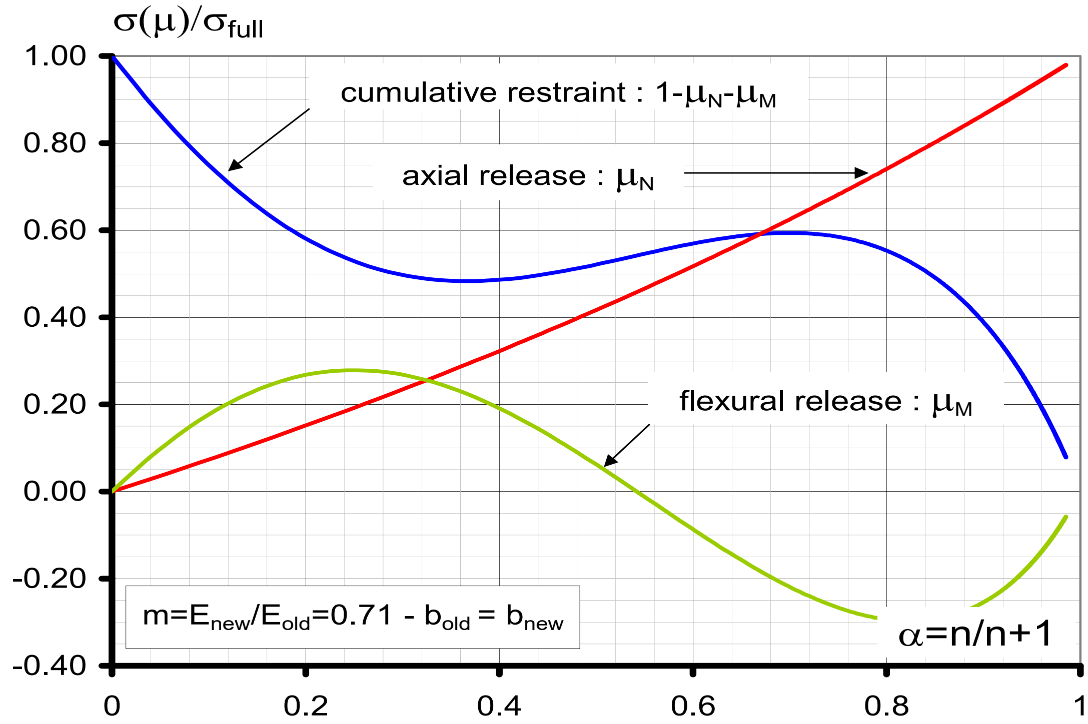
Centre of gravity of composite section (S = static moment)

$$W_2 = I_{comp} / y_2 = \frac{[I_{old} + A_{old}(cog - cog_{old})^2 + m \cdot (I_{new} + A_{new}(cog_{new} - cog)^2)]}{m \cdot (h_{old} - cog)}$$

With W_2: resisting moment of the composite section, at the level of the interface, I_{comp}: inertia of the composite section, y_2, lever arm between cog and interface (location of stress $\sigma_{new,2}$)

Degree of restraint

Bernard (2000) [1], Denarié et al. (2004) [4]



$$n = \frac{h_{new}}{h_{old}}$$

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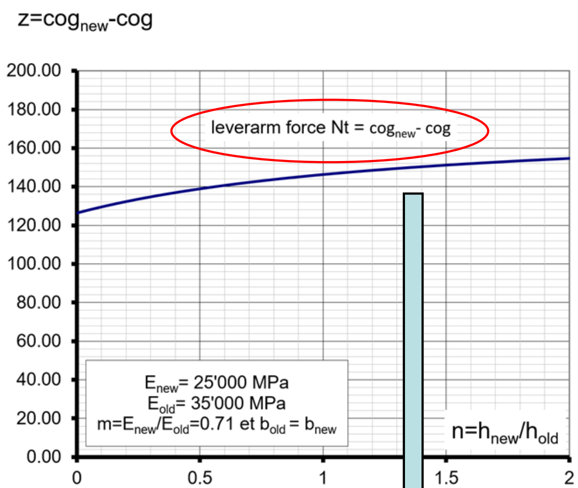
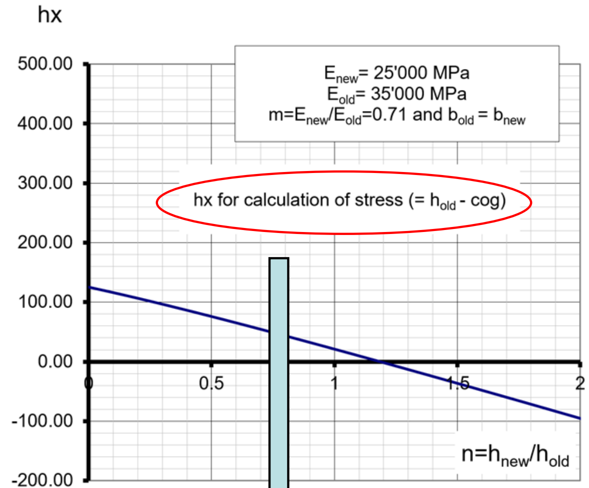
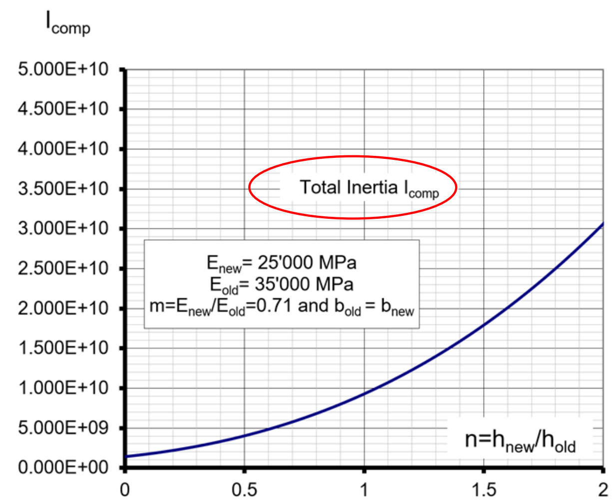






$$\mu_M = \frac{-\sigma_{M,2}}{\sigma_{full}} = \frac{N_t(cog_{new} - cog)}{W_2}\,\frac{1}{E_{new}.\varepsilon_{free.}}$$

$$= \frac{A_{new}\cdot(cog_{new} - cog)\cdot[m\cdot(h_{old} - cog)]}{[I_{old} + A_{old}(cog - cog_{old})^2 + m\cdot(I_{new} + A_{new}(cog_{new} - cog)^2)]} \Rightarrow = I_{comp}$$

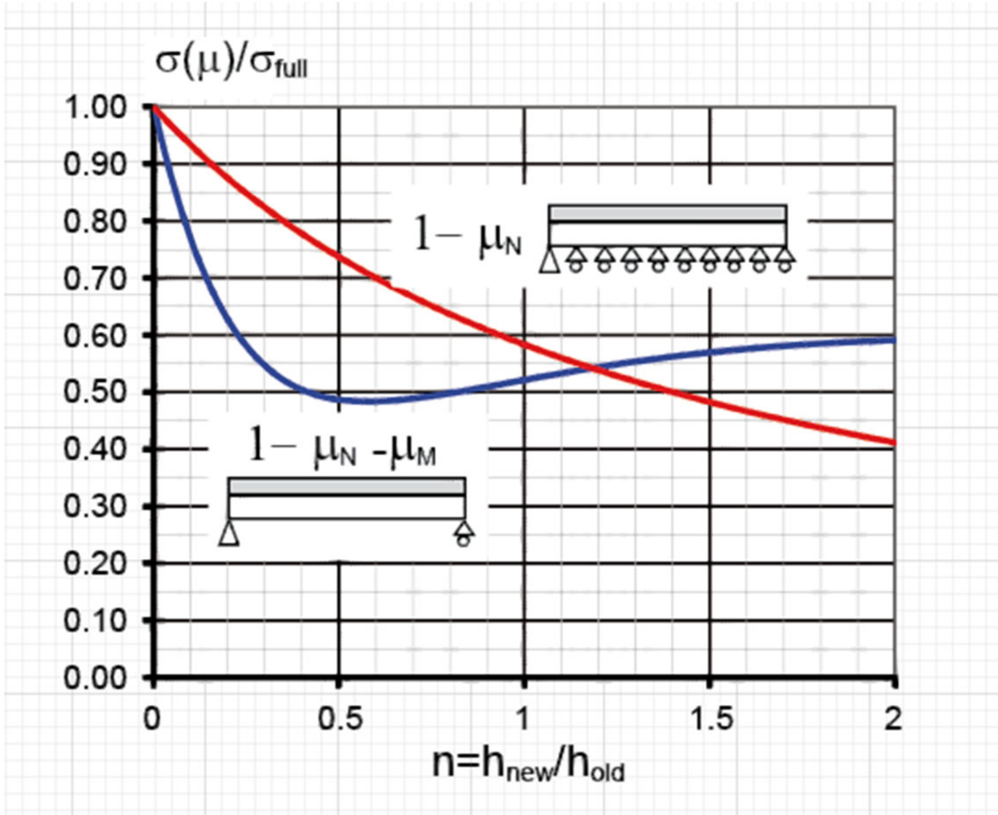
➔ Opposite effects on μ_M = non monotonic trend

Structural behaviour

Extensions possible to:

- Materials with creep/relaxation (secant modulus approach).
- Application to hyperstatic composite beams.
- Calculation of shear stresses at interface
- Effect of reinforcement in overlay
- Application to 3D (composite slabs)

Effect of static system on restraint



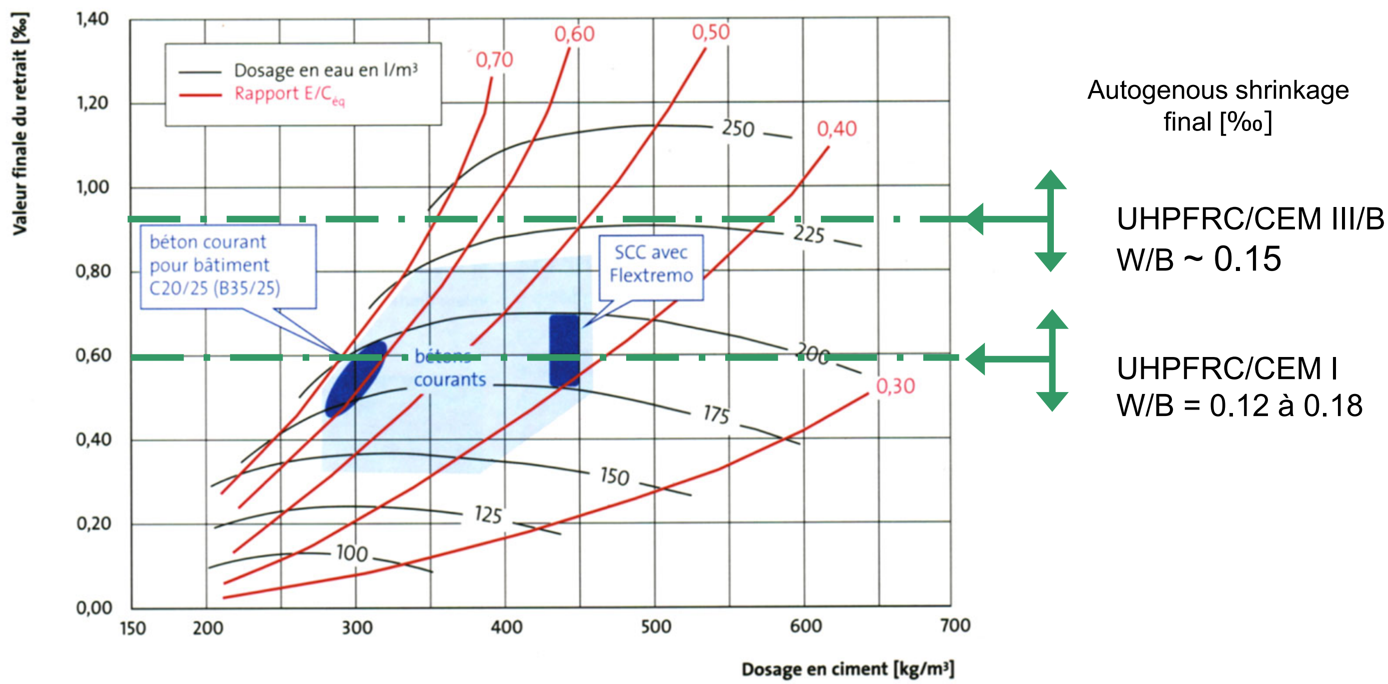
- UHPFRC cast over existing concrete
- E_{new}=50000 MPa
- E_{old}=35000 MPa

Denarié (2015)

3. Time-dependent response

- Purely elastic effect of restraint is mitigated by the viscoelastic response of cementitious materials under imposed déformations, at long term
- Imposed deformations (shrinkages) vary in terms of kinetics, time range of action and amplitude according to materials (effect of binders and dosage, w/c) and geometry of members (thickness, geometry, thermal and hygral boundary conditions)

FINAL SHRINKAGE OF VARIOUS CONCRETES, ADAPTED AFTER HOLCIM (2007)



No thermal treatment

➔ UHPFRC with CEM I : comparable to normal concretes or SCC

➔ UHPFRC with CEM III/B: higher than with CEM I

➔ Warning: UHPFRC shrinkage increases if poor curing at early age

Shrinkage types

Type	Origin	Acting on	Period
Plastic shrinkage	Premature drying	Fresh material	Setting time: 0-2/3 hours Concrete 8 to 36 hours for UHPC
Thermal deformation	Hydration heat	Curing and hardened material	0 to 7 days, longer depending on geometry (thickness)
Autogenous shrinkage	Chemical hydration reaction and self-drying (internal water consumption)	Curing and hardened material	Strong from 0 to 7 days (60 to 70%) and until hydration stabilizes (3 to 12 months)
Drying shrinkage	Drying (water exchange with the surrounding environment)	Hardened material	End of curing (7e day) until equilibrium with ambient environment (long-term)

Creep and relaxation

- VISCOELASTICITY: delayed response to loading, depending on loading history and age

  Creep: for an imposed force, displacement increases as a function of time.

- Relaxation: for an imposed displacement, the reaction force decreases as a function of time.

Degree of restraint – effect of creep

Silfwerbrand (2004) [3]

An engineering approach to estimate the effect of creep is to replace the modulus of elasticity E_{new} of the overlay with a fictitious modulus of elasticity $E_{new}^* = E_{new}/(1 + \varphi_{new})$ and E_{old} with $E_{old}^* = E_{old}/(1 + \varphi_{old})$ where, φ_{new} and φ_{old} are the creep coefficients of the overlay and base concrete, respectively.

$$\sigma_{new} = \frac{m^*(1-\alpha)\left(m^*(1-\alpha)^3 + \alpha^2(3+\alpha)\right)}{m^* + (m^*-1)\left(m^*(1-\alpha)^4 - \alpha^4\right)} \cdot \frac{E_{new}}{1+\varphi_{new}} \cdot \varepsilon_{\mathrm{free}} = \mu^* \cdot \frac{E_{new}}{1+\varphi_{new}} \cdot \varepsilon_{\mathrm{free}}$$

$$n = \frac{h_{new}}{h_{old}}$$

$$m^* = \frac{E_{old}^*}{E_{new}^*} = \frac{E_{old}/(1+\varphi_{old})}{E_{new}/(1+\varphi_{new})} = \frac{E_{old}}{E_{new}} \cdot \frac{1+\varphi_{new}}{1+\varphi_{old}} \approx 1 + \varphi_{new}$$

$$\alpha = \frac{n}{n+1}$$

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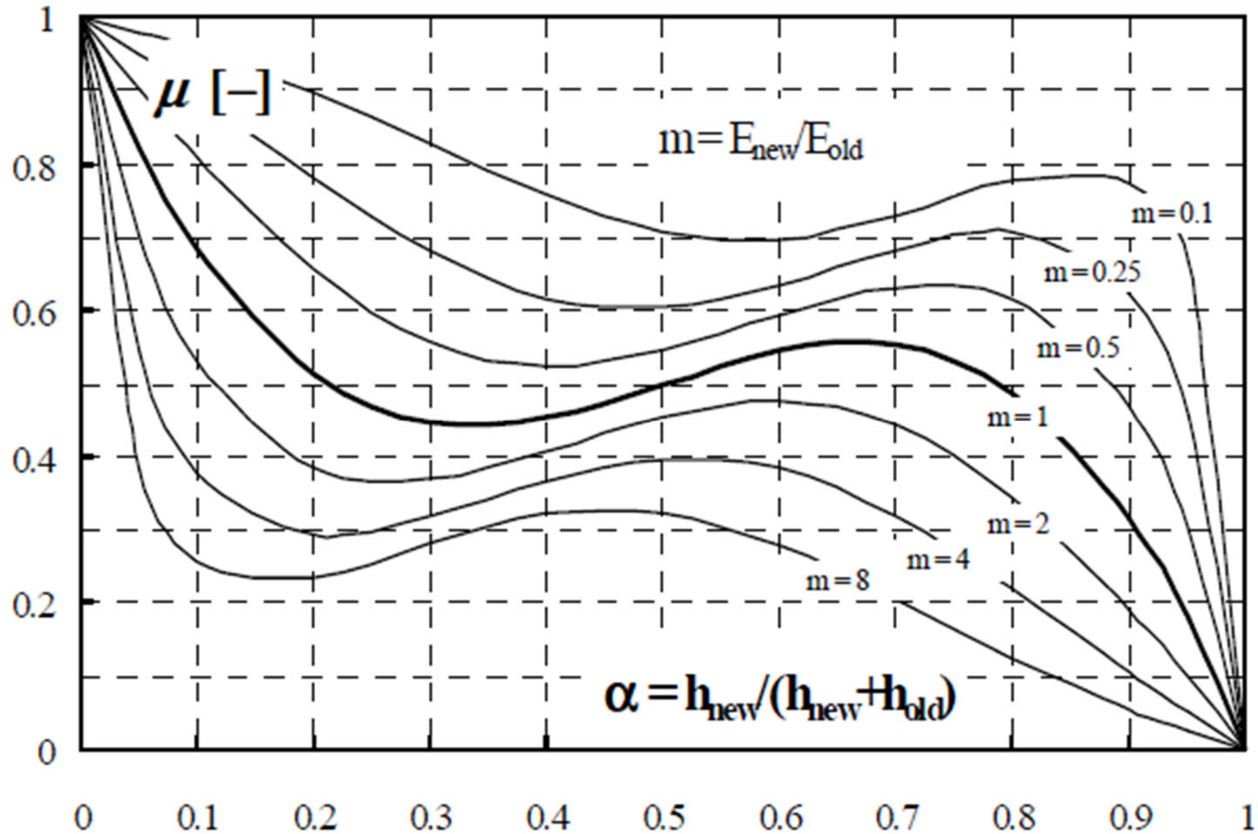
Degree of restraint – $b_{old}=b_{new}$

Silfwerbrand (2004) [3]



Example of calculation

Computation of stresses due to differential shrinkage in a repaired concrete beam.

Silfwerbrand (2004), in Denarié et al. (2004)

Geometrical and material data:
α =2/7 (≈ 0.286), E_{new} = E_{old} = 35 GPa, ε_{free} = 0.45 mm/m.
A)Full restraint μ = 1 → σ_{full} = E_{new} ε_{free} = 15.8 MPa.

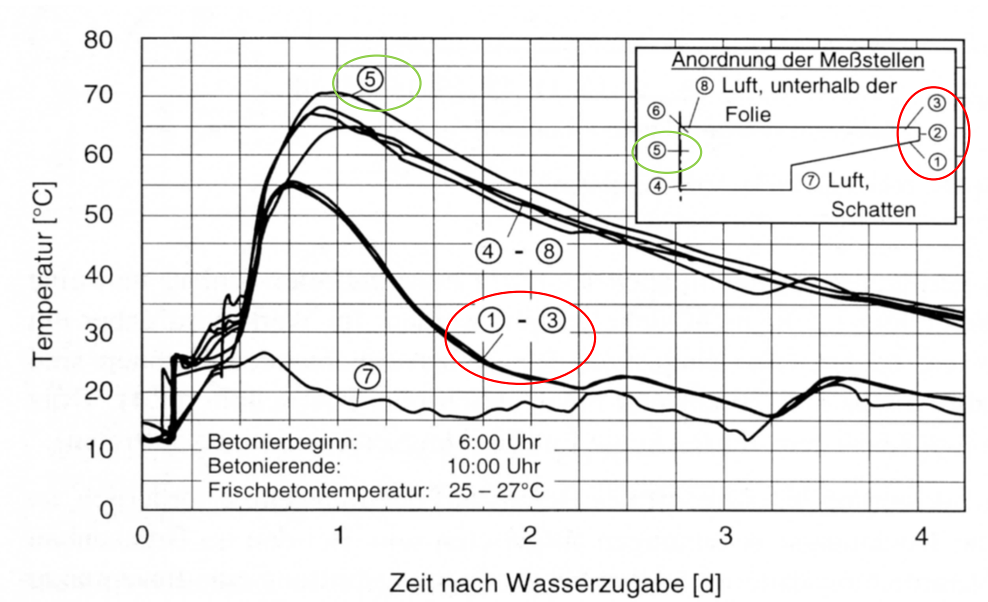
B)Beam theory with neglected creep → m = 1, μ = 0.452 and σ_{new} = 7.12 MPa.

C) Beam theory with creep coefficients ϕ_{new} = 4 and ϕ_{old} = 0 → m = 0.2, μ = 0.733, and σ_{new} = 2.31 MPa.

The maximum normal stress diminishes from 16 to 2.3 MPa. The latter value is of the same magnitude as the tensile strength of concrete. It explains why some overlays are crack-free while cracks are visible in others.

Other simplified model with $\sigma_{new} = \mu \cdot \frac{E_{new}}{1+\varphi_{new}} \cdot \varepsilon_{\text{free}}$ $\sigma_{new} = 0.452 \cdot \frac{35000}{1+4} \cdot 0.45/1000 = 1.42 MPa$

4. Thermal effects



König et al. (2001) [5]

Concrete C70/85
CEM I 42.5 R-HS,
dosage: 380 kg/m^3
Fly ash: 80 kg/m^3
D_{max}=16 mm
W/(C+0.4*CV)=0.3

➔ Local temperature rise depends on :boundary conditions (formwork, insulation, outside temperature)section geometry (thickness, etc.) binder heat release

Thermally induced cracking

https://www.csd.ch/fr/news/160202_flon

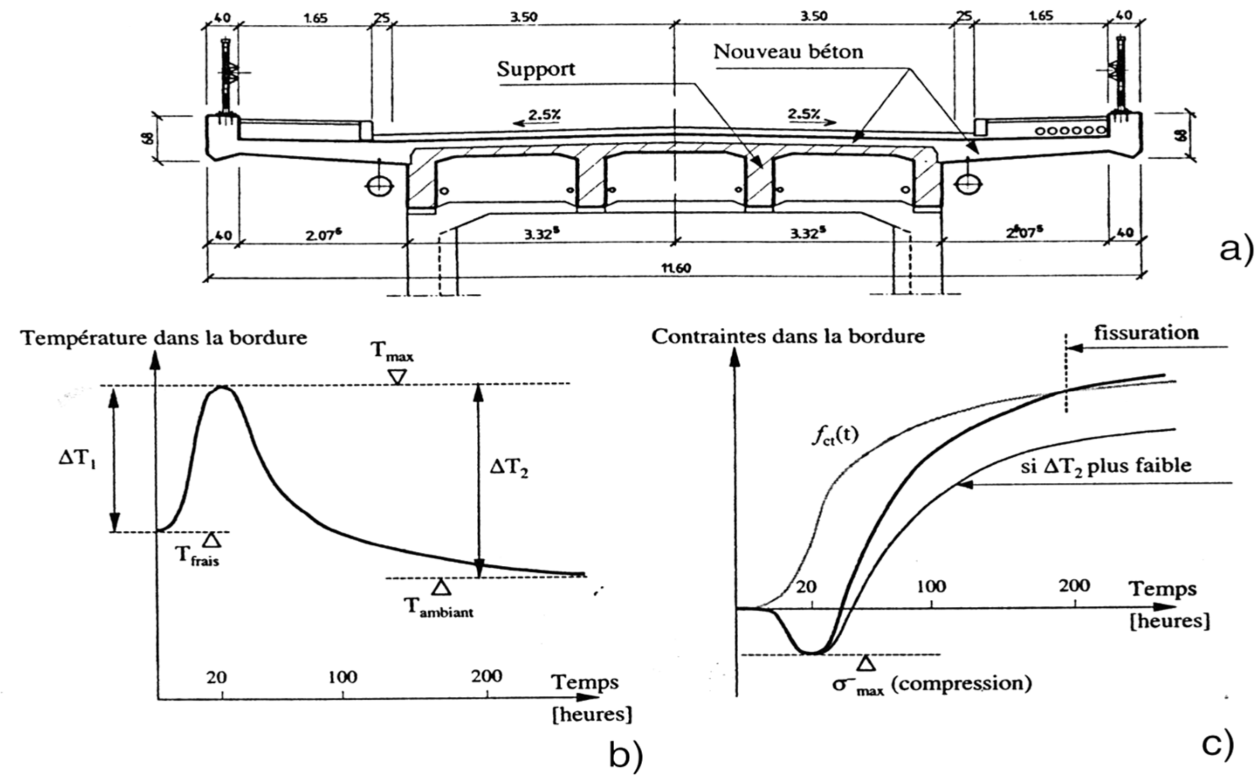
Arch bridge over le Flon, A9, lakeside exit Lausanne - Vennes

Monolithic crash barrier wall cast in 2016

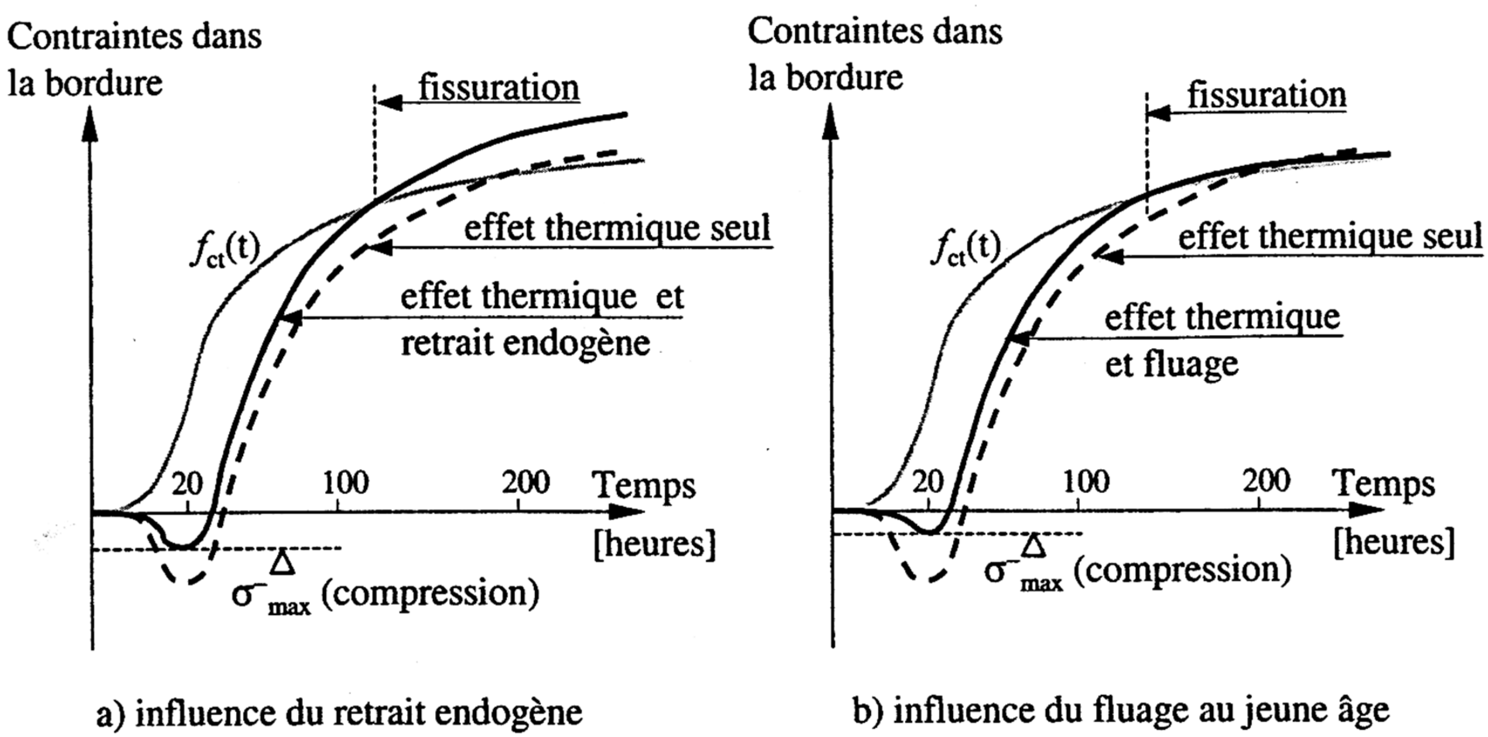
Concrete NPK G C35/45 after OFROU

Photos L. Sofia, 2019

- ➔ Vertical cracks, probably through, obviously due to thermal shrinkage + crazing due to poor curing (insufficient protection against premature drying) = poor management of cracking risks!
- ➔ See MCS/OFROU research report 82/97 (2001) [6]



Thermal effects at an early age - widening of the Javroz bridge, after Bernard (2000) [1]



Influence of autogenous shrinkage and creep at young age on the evolution of eigenstresses in new concrete, after Bernard (2000) [1].

➔It is therefore important:

1. to characterize the temperature difference between the substrate and the new concrete as a function of thermal boundary conditions and properties of the materials used,

2. to compare this temperature difference with a permissible value depending on the material and degree of restraint,

3. if necessary, to take actions if the maximum temperature difference exceeds the limit value.

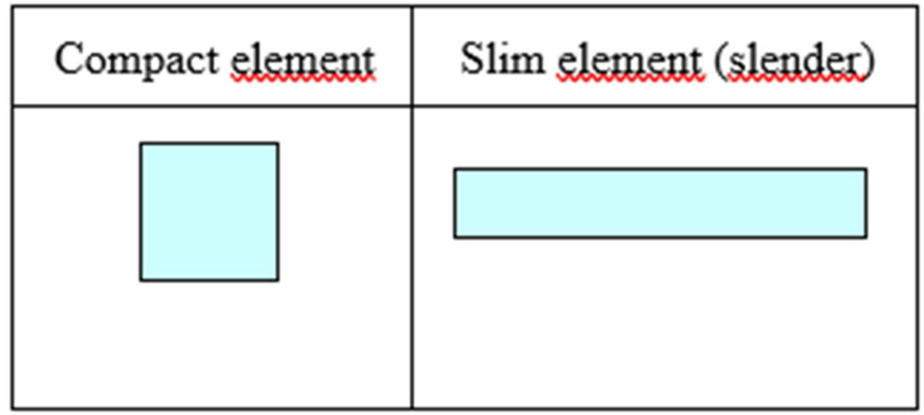
Factors influencing thermal effects

	Geometry/boundary conditions of the element	Cement fineness	Cement type and additions	Cement dosage	Water/binder ratio
Autogenous Shrinkage	___	___	++	+_	+++
Thermal effects (hydration)	+++	+++	+++	+++	+_

+++: *large effect;* ++: *fairly large effect;* +_: *small effect;* ___: *negligible effect;*

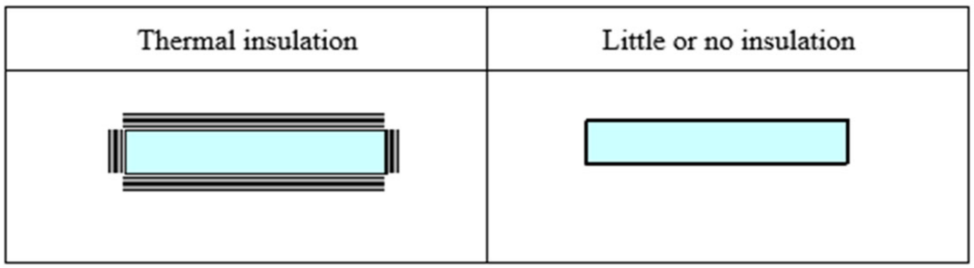
The two key effects at young age are hydration-related thermal effects and autogenous shrinkage. The greater the temperature difference between the substrate and the new concrete, and the greater the degree of restraint, the greater the risk of thermal through-cracking. Autogenous shrinkage, which depends little on cross-sectional geometry, is a further aggravating factor in these phenomena.

Effet of geometry



- The geometry of the new concrete section (surface-to-volume ratio), determines the element's inherent "heat loss" capacity. The more compact the element (low surface-to-volume ratio), the less quickly the heat created by the hydration process can escape to the outside, and the higher the temperature inside the element will be.

Effect of thermal boundary conditions

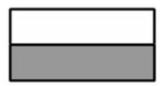


- normal formwork: $\pi_T = 2.5\ W/m^2/K$
- insulating formwork: $\pi_T = 0.5\ W/m^2/K$
- poorly insulating formwork $\pi_T = 5.0\ W/m^2/K$

Beware of the effect of wind on heat loss !

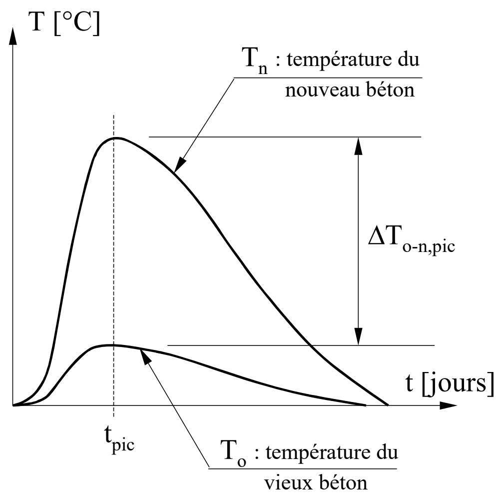
- Boundary conditions on surfaces in contact with the exterior (formwork and surface protection with varying degrees of thermal insulation).

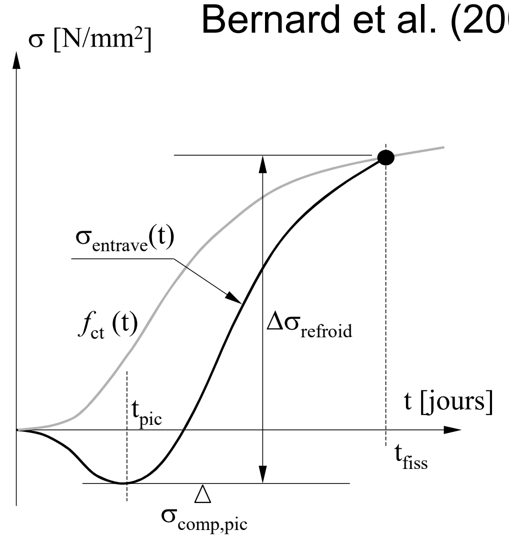
Effect of contact surface new-old material

A	B	C
Maximum contact surface (concrete-concrete)	Small contact surface (concrete-concrete)	Small contact surface (steel-concrete)
		

- Potential heat exchange between the supporting elements (old) and the new concrete. The larger the contact surfaces between the 2 elements, the greater the heat exchange and the smaller the temperature difference. It should be noted that cases B and C are very similar (low temperature rise in the substrate) and clearly differ from case A, where the temperature rise in the substrate is marked due to the heat released by the new concrete.

5. Simplified approach to limit thermal cracking





Bernard et al. (2001) [6]

- New concrete applied on existing support
- Average degree of restraint μ for new layer
- t_{pic} varies between 20 and 30 hours and t_{fiss} between 5 and 7 days

$\Delta T_{o\text{-}n,pic}$:	temperature difference between old and new concrete at time t_{pic}
$\Delta T_{o\text{-}n,fiss}$:	temperature difference between old and new concrete at time t_{fiss}
$\bar{E}_{ct}$:	average modulus of elasticity of new concrete between t_{pic} and t_{fiss}
$\bar{\alpha}_T$:	average coefficient of thermal expansion between t_{pic} and t_{fiss}
$f_{ct,new}$ (t_{fiss}):	tensile strength of new concrete at time t_{fiss} .

$$\Delta\sigma_{refroid}(t_{fiss}) = \left[\Delta T_{0-n,pic} - \Delta T_{0-n,fiss}\right]\bar{\mu}\bar{E}_{ct}\bar{\alpha}_T$$

Non cracking condition $$\Delta\sigma_{refroid}(t_{fiss}) - \sigma_{comp,pic} \leq f_{ct,new}(t_{fiss})$$

Bernard et al. (2001) [6]

Simplifications

- the influence of autogenous shrinkage and early age creep (unfavorable) is taken into account, assuming that the value of $\sigma_{comp,pic}$ (favorable) is zero.
- the contribution of $\Delta T_{o\text{-}n,fiss}$ which, at time t_{fiss} , is small, is neglected.
- the average modulus of elasticity of the new concrete E_{ct} corresponds to the value of the modulus measured at an age of three days and the coefficient of thermal expansion α_T is constant between t_{pic} and t_{fiss} .

$$\Delta T_{0-n,adm} = \frac{f_{ct,new}(t_{fiss})}{\overline{\mu} E_{ct,3} \alpha_T}$$

Example: $f_{ct,new}(t_{fiss})$=2.5 N/mm^2, μ=0.75, $E_{ct,3}$ =28000 N/mm^2, α_T = 10^{-5} 1/C

$$\Delta T_{0-n,adm} = \frac{2.5\, N/mm^2}{0.75 \cdot 28'000\, N/mm^2 \cdot 10^{-5} {}^\circ C^{-1}} = 12^\circ C$$

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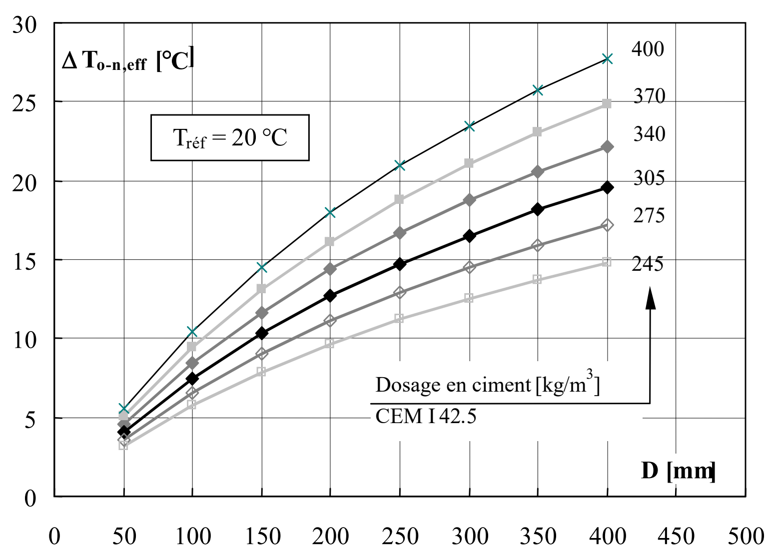
- The definition of the limit value $\Delta T_{o\text{-}n,adm}$ enables us to establish a simplified approach for verifying the influence of early-age hydration effects on the cracking of hybrid elements. This involves determining the effective value $\Delta T_{o\text{-}n,eff}$ of the maximum temperature difference between old and new concrete during hydration of the new section of a given hybrid element. The value of $\Delta T_{o\text{-}n,eff}$ is generally that which is measurable at the time of the temperature peak. The following inequality must be thus verified:

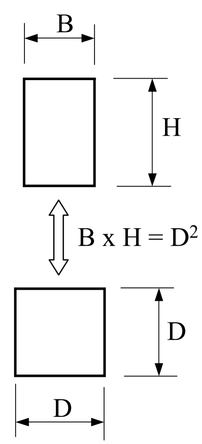
$$\Delta T_{o-n,eff} \leq \Delta T_{o-n,adm}$$

- The advantage of this simplified approach is that it allows the designer to perform only thermal calculations, and all aspects related to the aging mechanical behavior of concrete are synthesized in the value of $\Delta T_{o\text{-}n,adm}$.
- This approach is mainly applicable when predimensioning hybrid structures. It can also be used to determine whether any constructive measures need to be taken, or whether a more in-depth numerical study using FEM analysis tools.

Calculation charts

Bernard et al. (2001) [6]





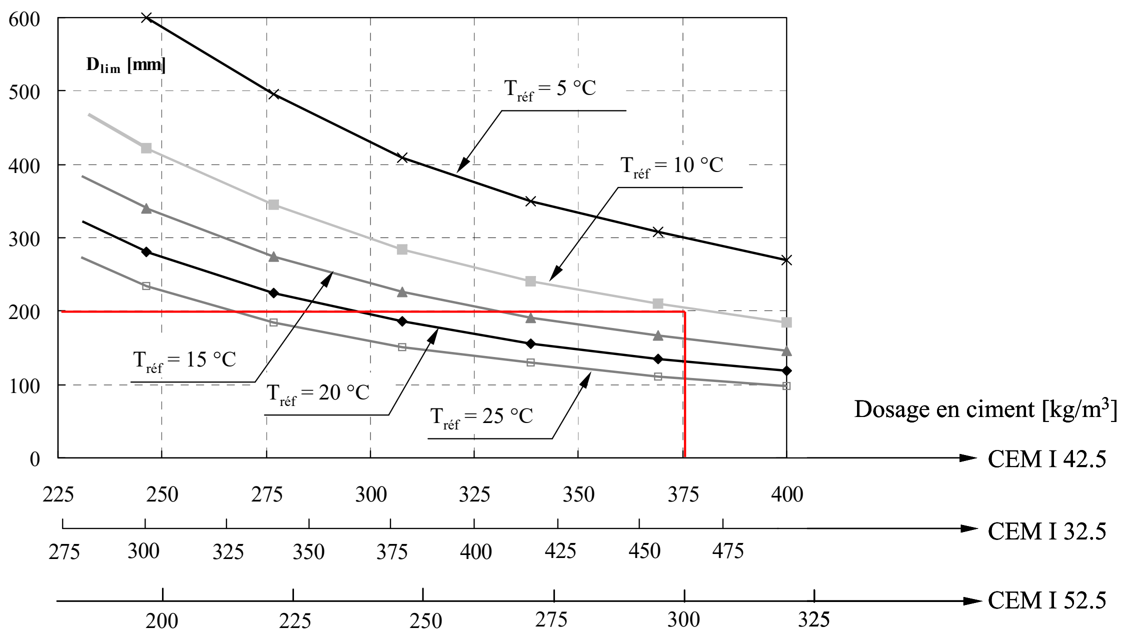
Calculations with FEM tools
CEM I 42.5
Wooden formwork (π_T =3.5 W/m^2K)
Equivalent square cross section

$T_{ref} = (T_{fresh} + T_{external})/2$

- Estimation of maximum temperature difference by FEM

Predesign charts - generalization

Bernard et al. (2001) [6]



$$\Delta T_{o-n,eff} = \Delta T_{o-n,adm}$$

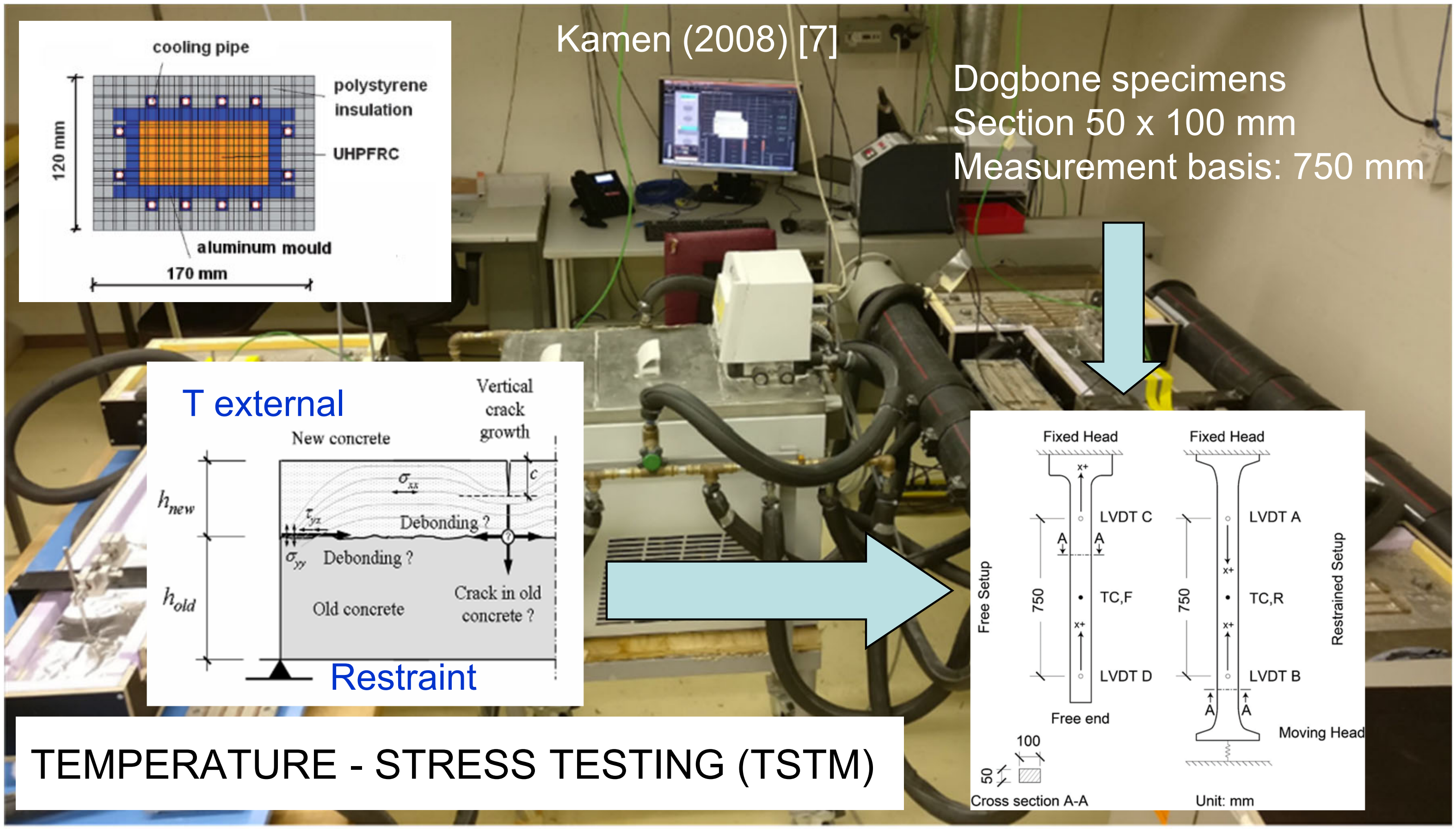
For D_{lim}

$T_{ref} = (T_{fresh} + T_{external})/2$

Example: 375 kg/m³ CEM I 42.5
T_{ref}=10° C, D_{lim}=200 mm

- Limit geometry D_{lim} above which cracking is likely

6. Thermomechanical effects in UHPFRC layers under restraint

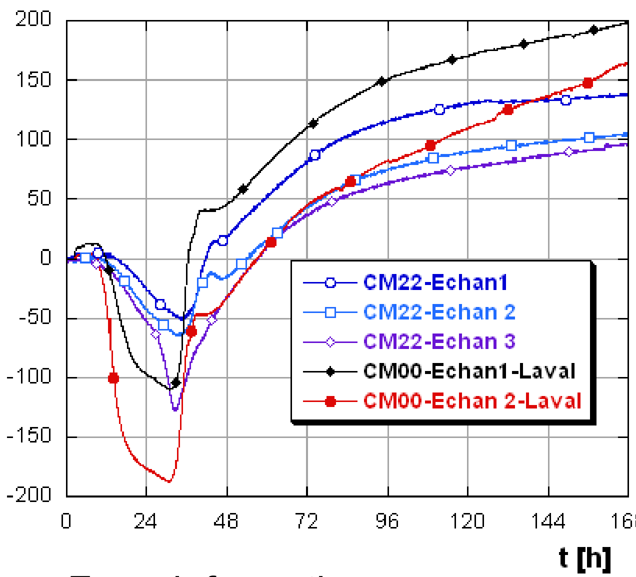


TSTM SET-UP AT MCS/EPFL

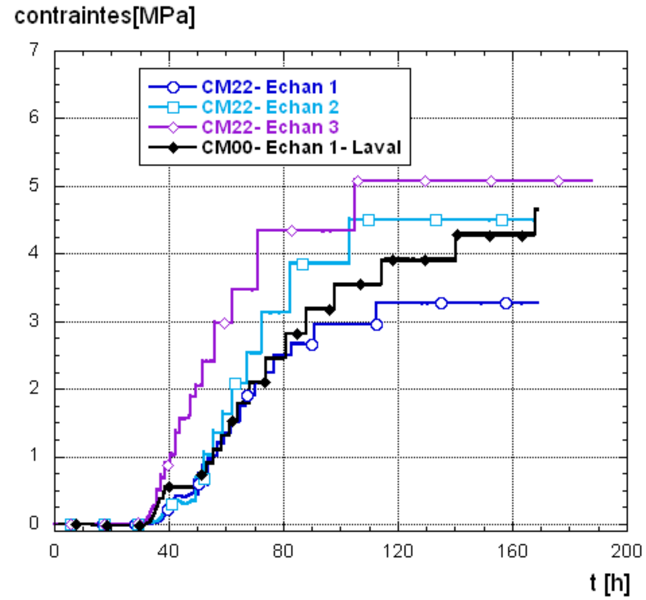
- Optimized for UHPFRC
- Incremental creep tests
- Stroke blocked (passive) or full restraint
- Creep tests
- Relaxation tests

- Isotherm material response
- « Experimental simulation » of complex load cases (restraint and temperature)

INCREMENTAL CREEP TESTS (FULL RESTRAINT)



Free deformations

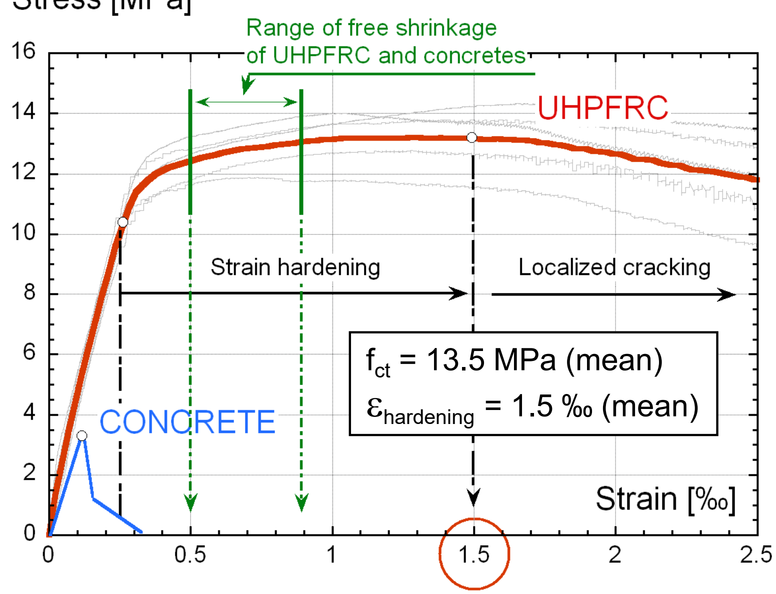


Eigenstresses

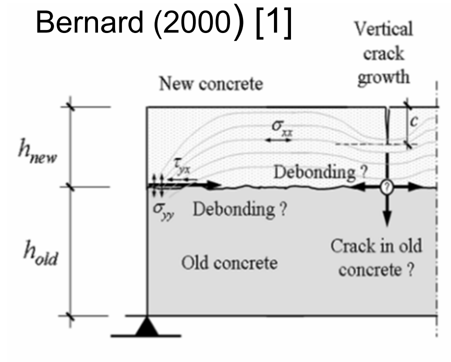
➔Good reproductibility of test results between different set-ups
➔Eigenstresses at early age under full restraint in the range of 4 MPa

UHPFRC - after Kamen (2007) [7]

Deformation balance



Bernard (2000) [1]



➔ Build up of eigenstresses due to restrained shrinkage

➔ Relaxation of eigenstresses by factor >2, thanks to UHPFRC viscous response

➔ Restraint < 100 % (50 to 90 %) upon composite structural member (stiffness ratio between new and old layers)

- ➔ Deformation capability very favourable for UHPFRC
- ➔ (Viscous + strain hardening deformations) > restrained shrinkage
- ➔ E modulus 30 % higher than usual concretes
- ➔ Tensile strength 3 to 4 times larger than usual concretes
- ➔ Avoid macrocracks at SLS, in structures

MODELLING – MLS/FEMMASSE

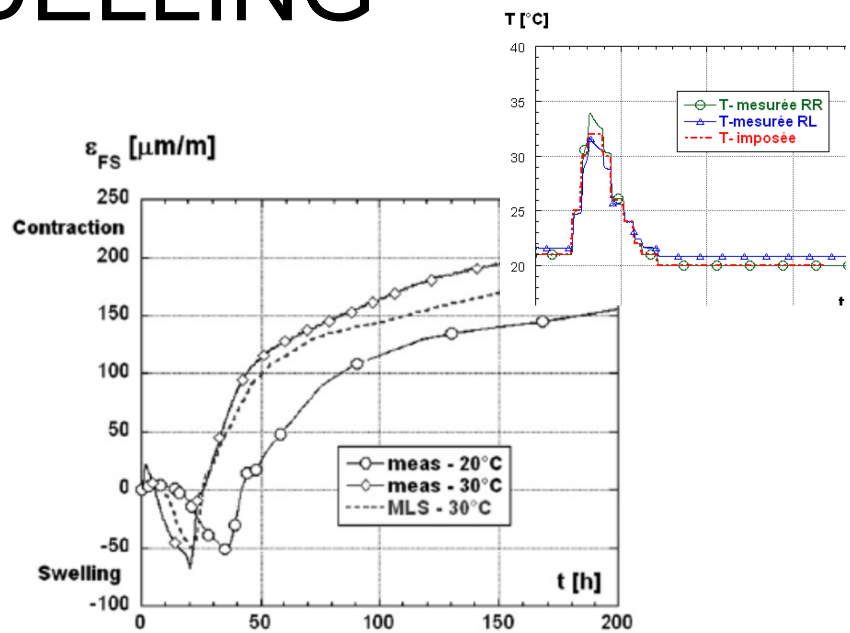
Kamen (2007) [7]

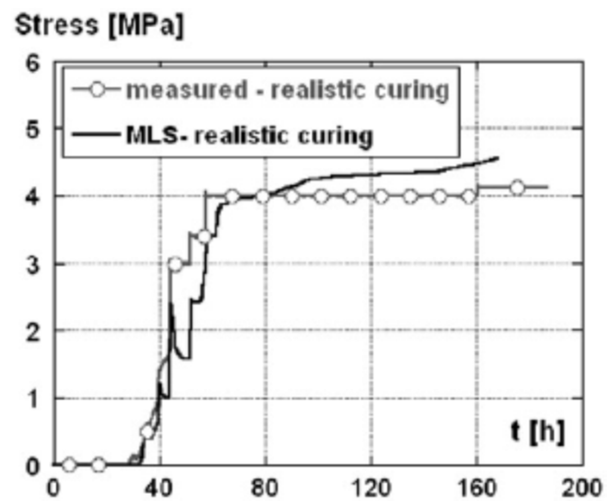
- Maturity after Arrhenius – M(t)

$Q/R=Q_0/R$ and $+\Delta Q/R(20-T)$ if $T<20°$ C

- User input for free autogenous shrinkage
- Ageing generalised Maxwell chains
- User input for thermal dilation coeff.
- All material laws function of M(t)
- Multilinear smeared crack model if needed

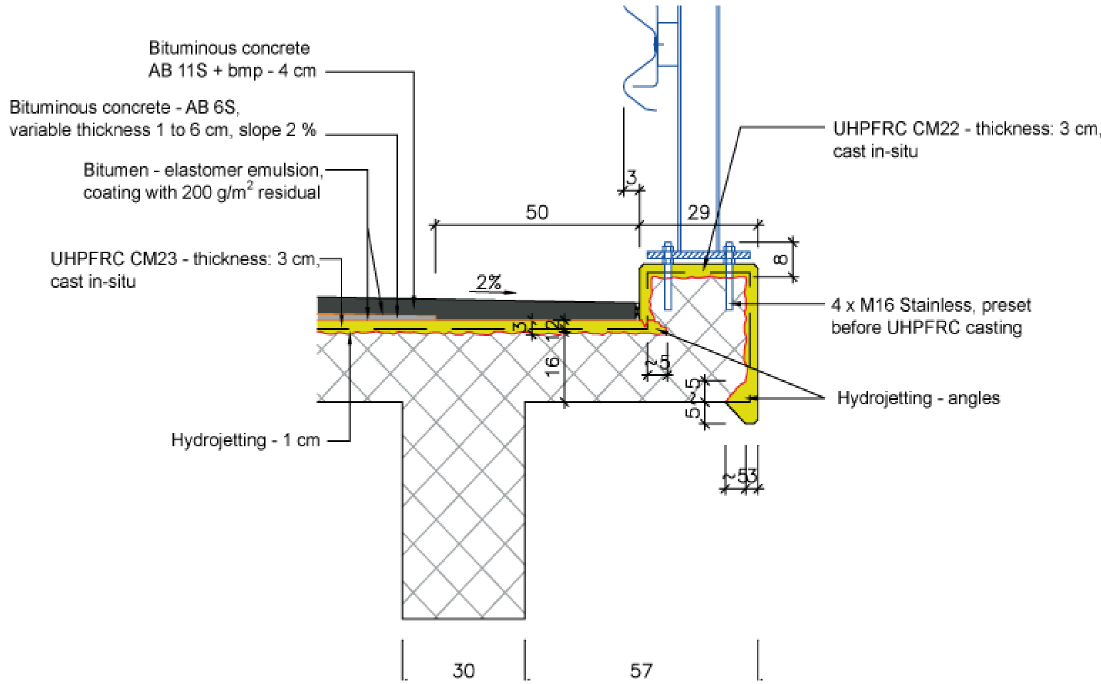
MODELLING





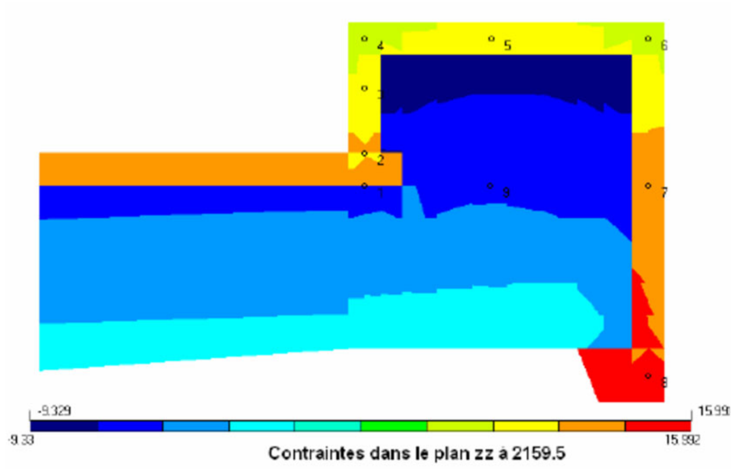
➔Realistic temperature history for 10 cm UHPFRC overlay
➔Free deformations were used to determine TDC
➔Prediction of model corresponds for free deformations and stresses

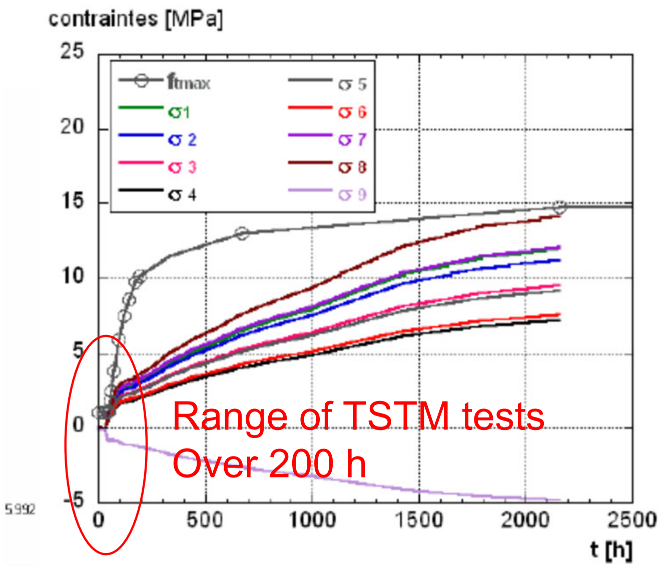
APPLICATION TO BRIDGE CURB



➔ 3 cm UHPFRC applied to protect existing curb

APPLICATION TO BRIDGE CURB





Out of plane stresses σzz
Full restraint out of plane
External temperature: 20 ° C

Kamen (2007) [7]

➔Signficant eigenstresses under full restraint at 20 ° C external temperature
➔Maximum ΔT in UHPFRC = 4° C
➔Stresses close to 10 MPa – entering hardening domain of UHPFRC
➔Positive effect of restraint < 100 %
➔Possible effect of low temperatures (5 to 10 ° C) unknown.

7. Mitigation methods against thermal cracking risk

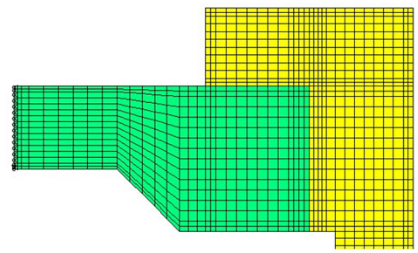
- Decrease heat of hydration of concrete: use of mineral additions such as fly ash, decrease heat of hydration of cement such as slag cement or coarser cement
- Cool down concrete: ice, liquid nitrogen
- Cool down the new members internally by means of cooling circuits (pipes) optimized by FEM calculations
- Combinations of methods

➔ Most often decreasing heat of hydration is not sufficient

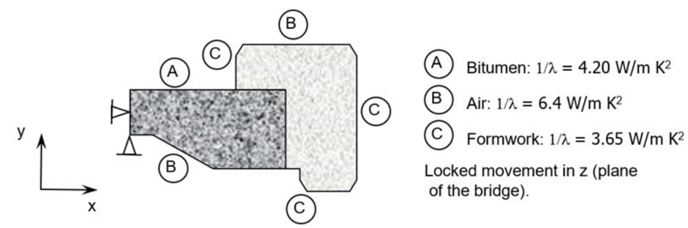
➔ Risk also dependent on season of casting

Bessières bridge Lausanne (2003)

- Mesh



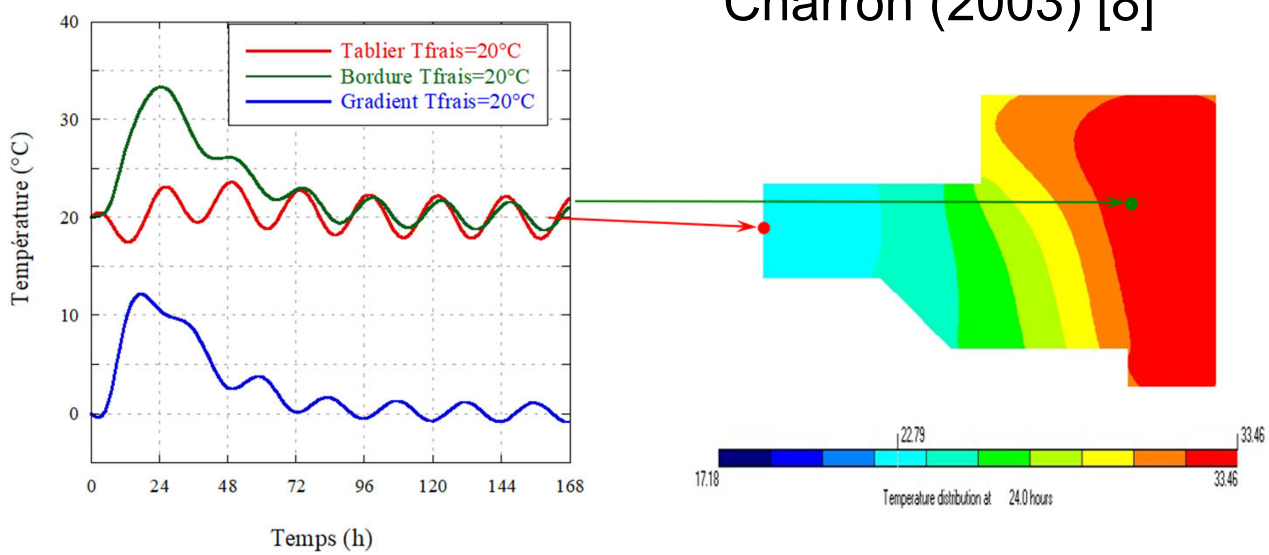
- Boundary conditions



- Thermomechanical analyses by FEM – Charron (2003) [8]
- Age and temperature dependent mechanical and thermal properties

- Temperature variation in edge and apron for T =20°C$_{frais}$

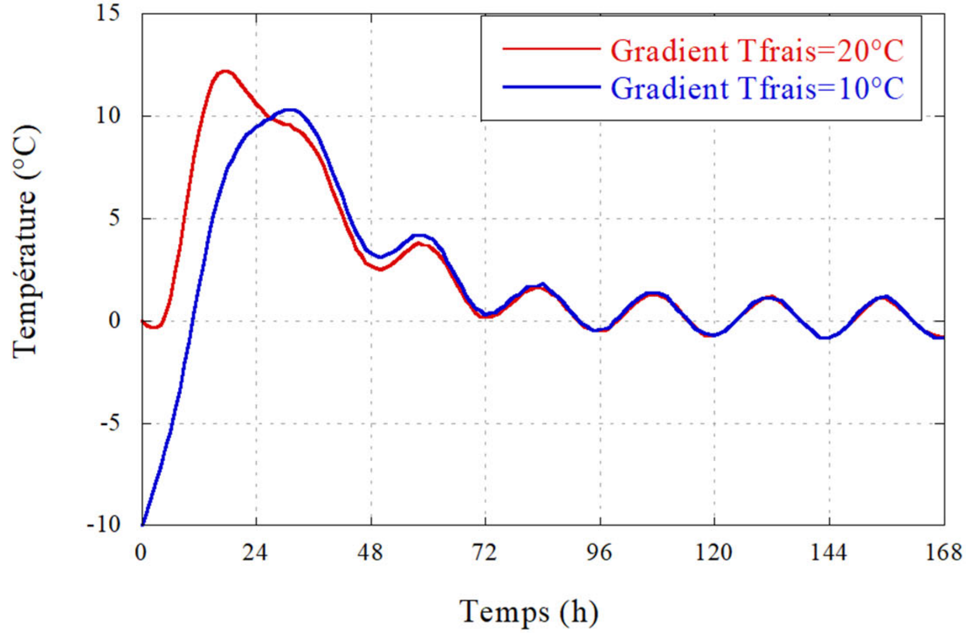
Charron (2003) [8]



- Without concrete cooling
- Temperature gradient reaches 12° C
- Risk of cracking

  - Daily temperature variation: +/- 6°C

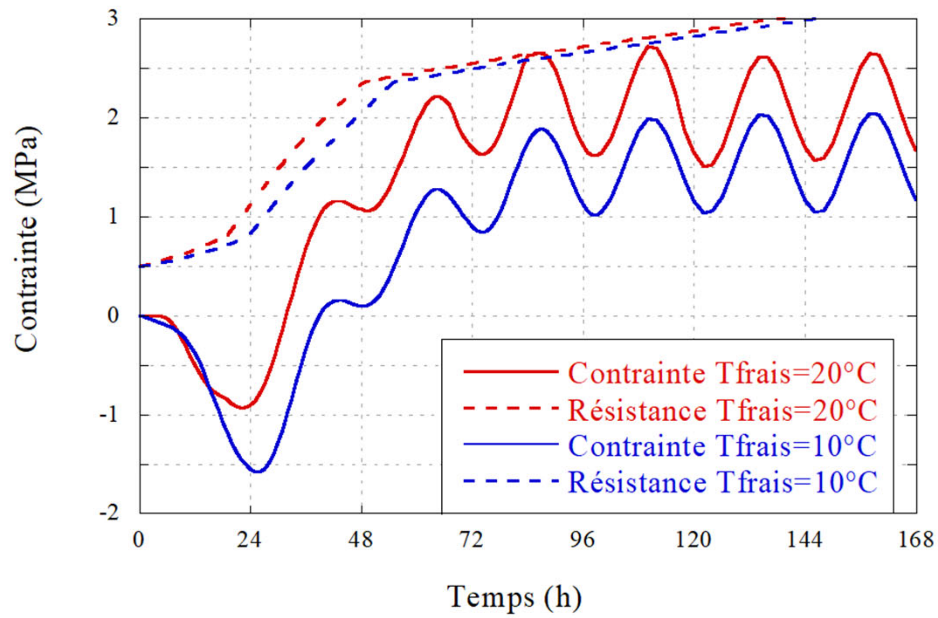
- Temperature gradient between edge and deck according to T_{frais}



Charron (2003) [8]

➔ limit temperature gradient to less than 12° C, Bernard (2000)

• Induced stress at edge core according to T_{frais}



Charron (2003) [8]

- Decrease of eigenstresses due to concrete cooling, below cracking threshold
- Effect of concrete cooling on kinetics of development of mechanical properties

Rehabilitation

Charron (2003) [8]

- Preparation

June 2003: very hot temperatures
Concrete with fly ash

Rehabilitation

Charron (2003) [8]

- Cooling

- Concrete cooling with liquid nitrogen

Rehabilitation

Charron (2003) [8]

- Installation

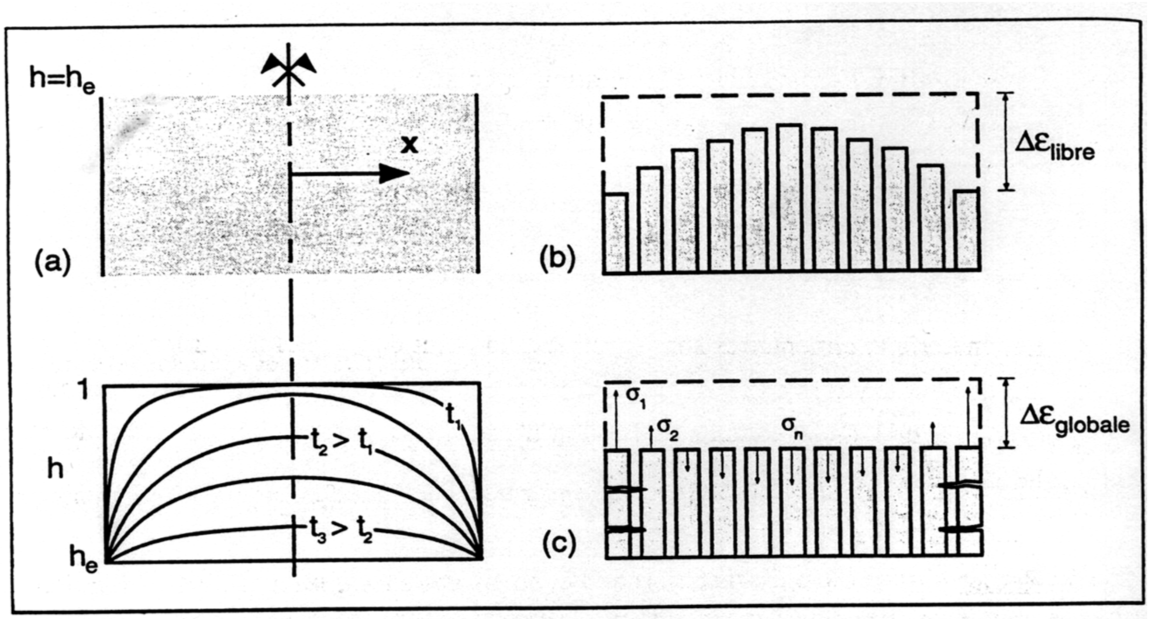
- Casting of the concrete

- Cracking survey

Charron (2003) [8]

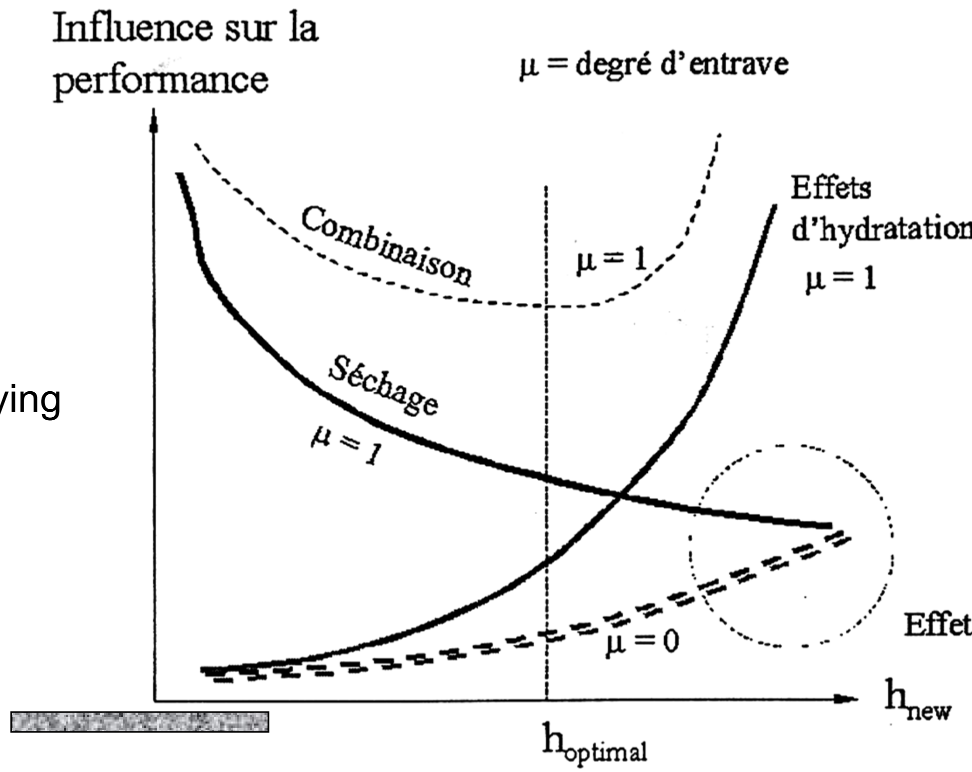
- Some cracks…
- Concrete placing was too long – cooling benefits lost

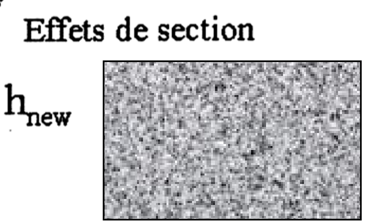
8. Effect of moisture gradients



Desiccation of a symmetrical concrete element exposed to a moisture gradient h_e ; a) isohygron curves versus time, b) free shrinkage of elementary layers for a given moisture profile, c) overall shrinkage, induced stresses and resulting skin cracking, after Bazant (1982) [9].

Séchage = drying





Thin members = more sensitive to drying

Thick members = more sensitive to thermal effects

Very different kinetics of drying and cooling down

Also function of boundary conditions

Influence of new concrete thickness on the performance of hybrid elements, after Bernard (2000) [1]

9. Synthesis

- Consider real restraint in assessments of cracking risk
- Viscolelasticity mitigates developement of eigenstresses
- Simplified model of thermal cracking risk in terms of admissible temperature gradient
- Mitigation of thermal cracking risk with choice of concrete composition and concrete cooling
- Upon needs , FEM analyses for detailed studies
- Different kinetics for drying and cooling processes
- Cracking risk process according to layer thickness

10. References

[1]. Bernard O., (2000), "Comportement à long terme des éléments de structure formés de bétons d'âges différents", thèse EPFL n° 2283, 2000.

[2]. Bissonnette B., (1996), "Le fluage en traction: un aspect important de la problématique des réparations minces en béton", Thèse de Doctorat, CRIB, Université Laval, Québec, Canada.

[3]. Silfwerbrand, J., (1997) “Concrete Overlays.” Report No. 10, 3rd Edition, Chair of Structural Mechanics and Engineering, Dept. of Structural Engineering, Royal Institute of Technology, Stockholm, Sweden, 65 pp. (In Swedish).

[4]. Denarié E., Silfwerbrand J., Beushausen H., (2004), “Structural behaviour“, Chapter 5 of State of the Art Report, RILEM TC 193-RLS, RILEM.

[5]. König G., Viet Tue N., Zink M., (2001), "Hochleistungsbeton - Bemessung, Herstellung und Anwendung", *Ernst & Sohn*.

[6]. Bernard O., Denarié E., Brühwiler E., (2001), "Comportement au jeune âge du béton et limitation de la fissuration traversante des structures hybrides", OFROU 82/97, pp. 89-102.

[7]. Kamen A., Denarié E., Sadouki H., Brühwiler E., (2008), “Thermo-mechanical response of UHPFRC at early age - experimental study and numerical simulation”, Cement and Concrete Research, vol. 38,, pp. 822-831

[8]. Charron J.P., Denarié E., Brühwiler E., (2003), "Prévention des fissures traversantes pour le bétonnage des bordures du pont Bessières", Bulletin technique de la Suisse Romande, Traçés, 21: 17-23, (in French).

[9]. Bažant, Z. P. (1982), "Mathematical models for creep and shrinkage of concrete", in Bazant, Z.P. and Wittmann, F.H. (Eds.): Creep and Shrinkage in Concrete Structures, pp.163–256, John Wiley & Sons.