American Concrete Institute

Fire Behavior of Post-Installed Anchoring Systems

Nicolas Pinoteau, Kenton McBride, Omar Al-Mansouri

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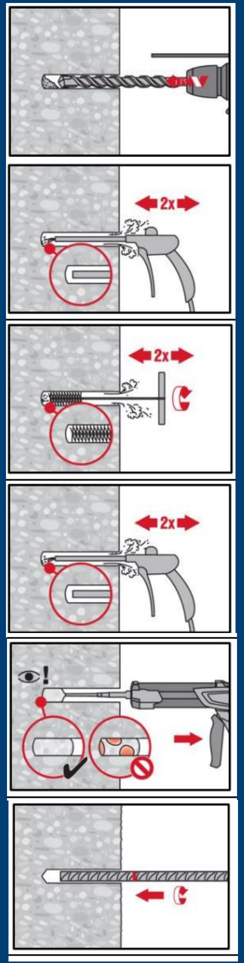
HILTI

Introduction

Description of a post-installed reinforcing bar



- Drilling to the required embedment depth
- Cleaning of the hole
- Injection of the adhesive in the hole
- Installation of the reinforcing bar

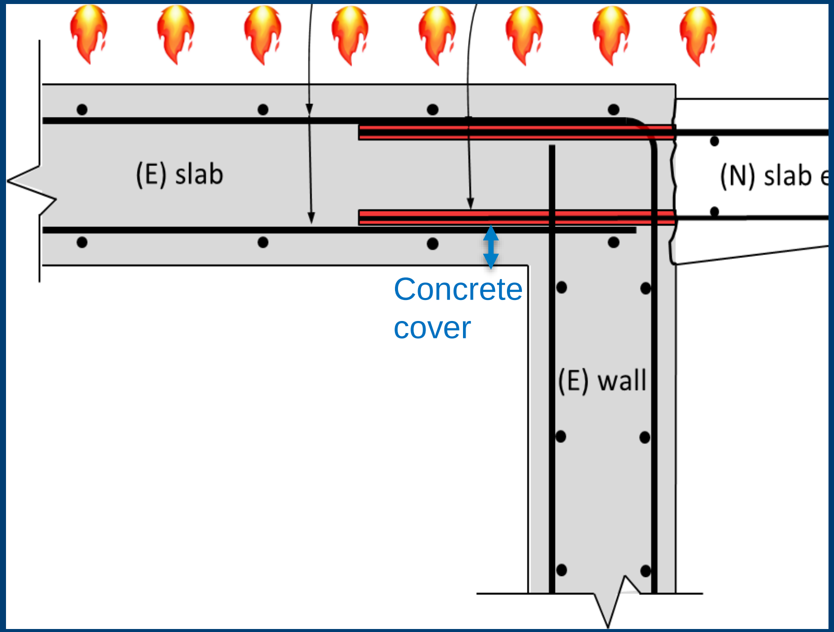
Fire demand on reinforcing bars

International Building Code

Cast-in reinforcement for concrete is covered by fire-resistance-rated design of structural elements .

The minimum thickness of concrete cover is provided in the IBC with prescriptive values depending on:

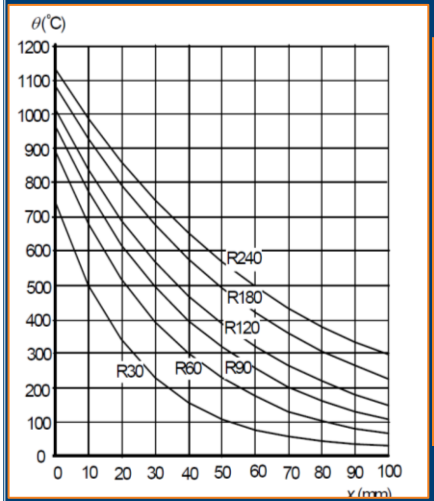
- Fire rating
- Type of concrete
- Type of structural element

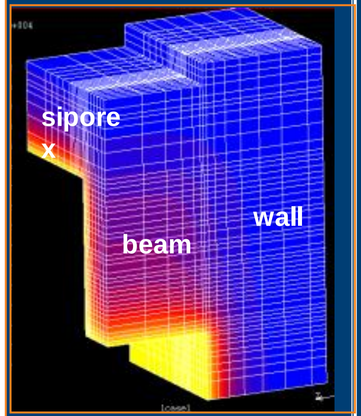


The three-step method in Europe

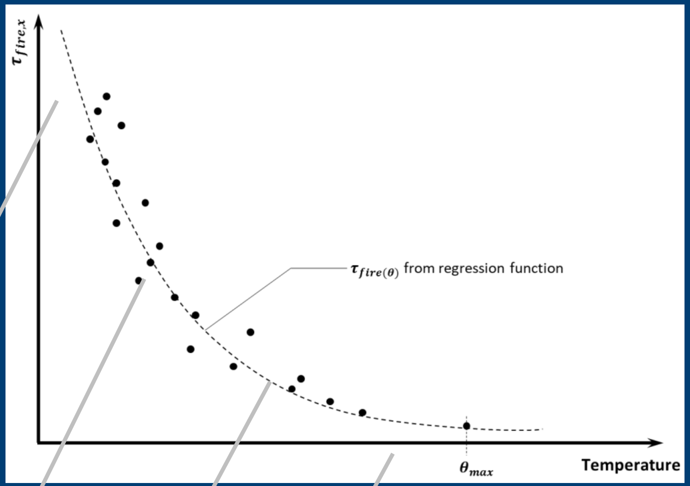
European Assessment Document 330087

Temperature distribution



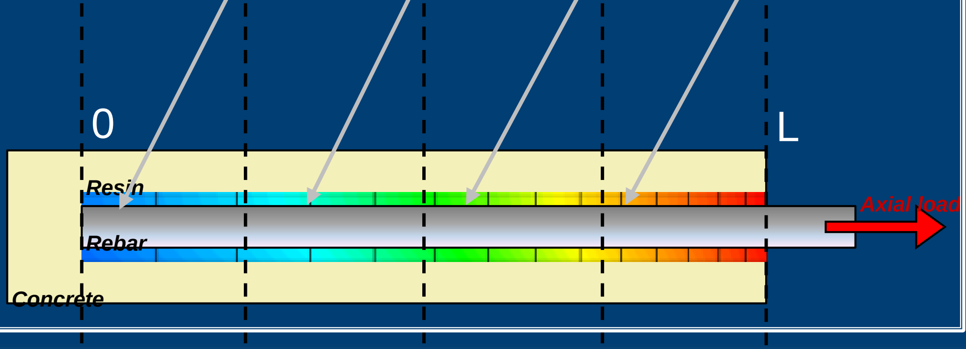


Bond strength – temperature relationship



Load-bearing capacity by integration of bond resistance

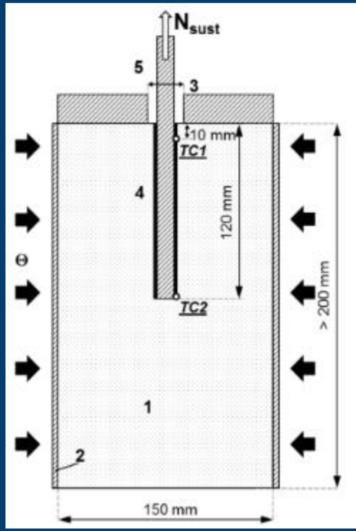
$$F_{fire} = \pi d \int_0^L \tau_{fire}(\theta) \cdot dx$$

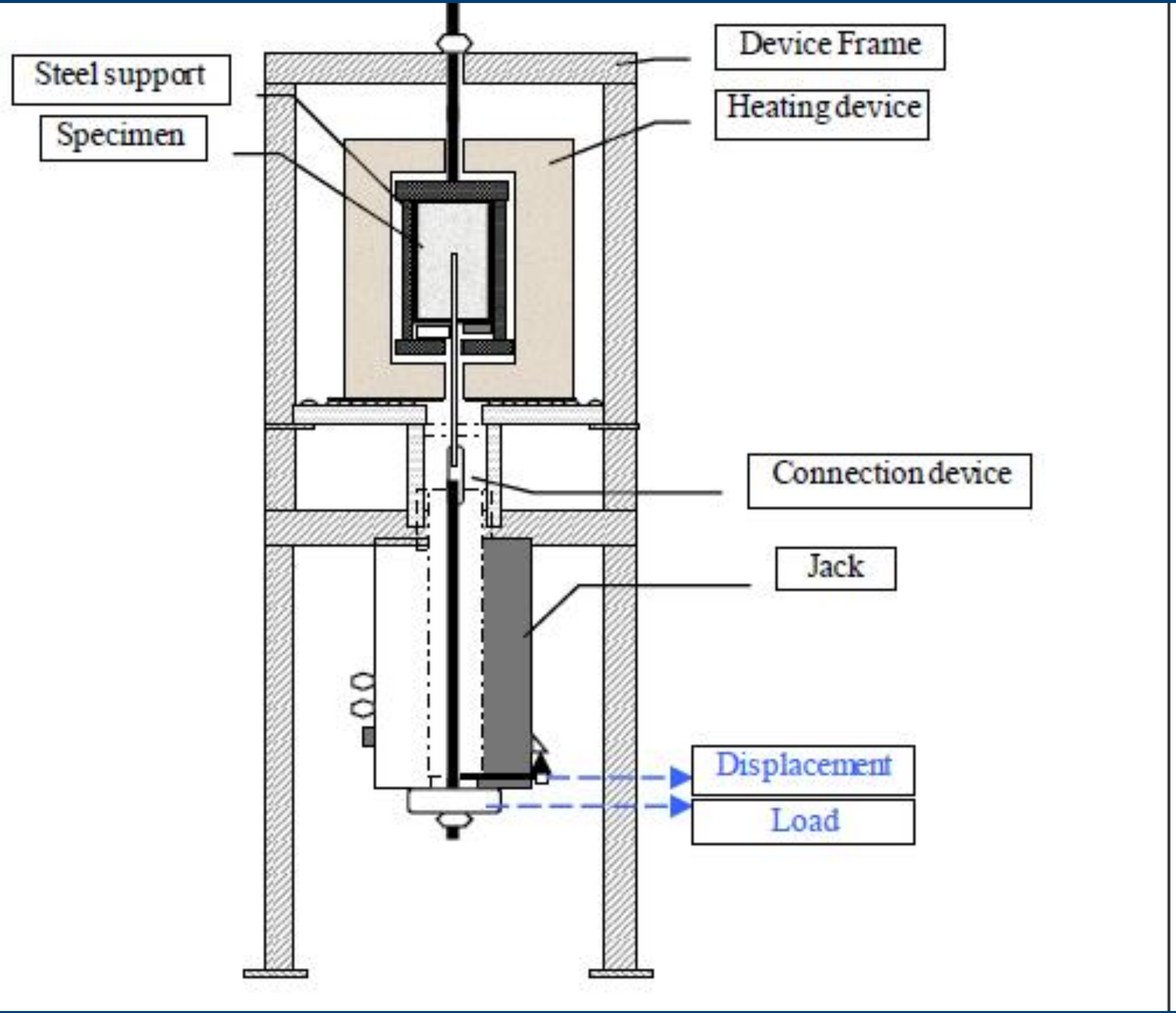


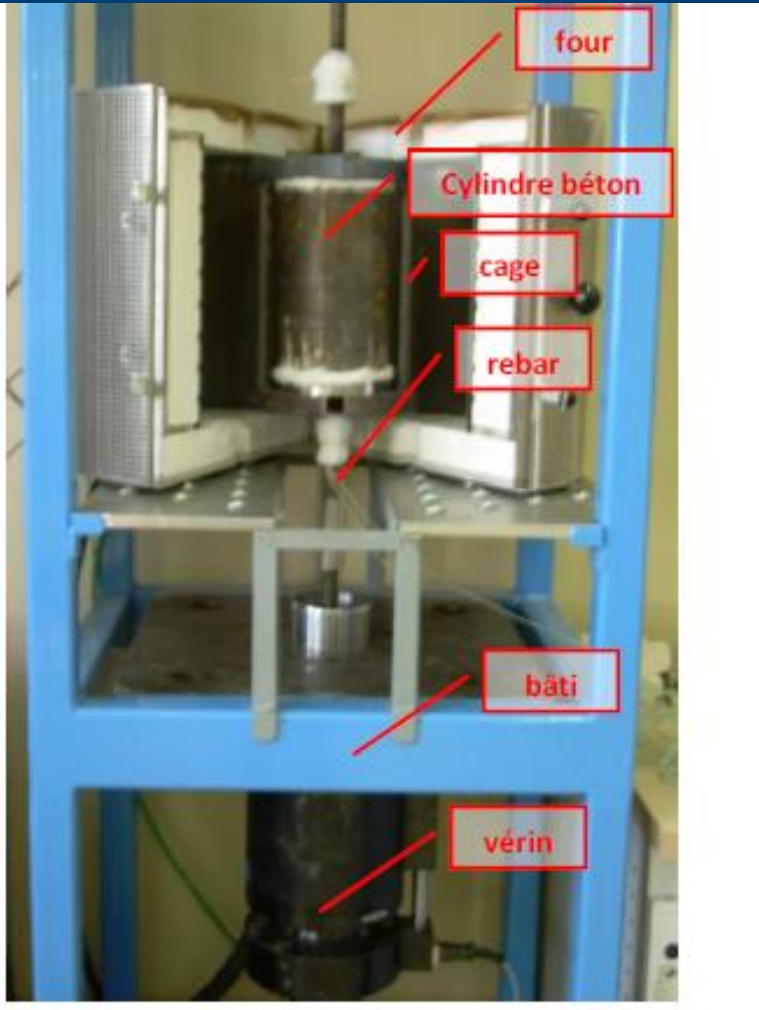
I. Product Evaluation

II. Validation of the Method

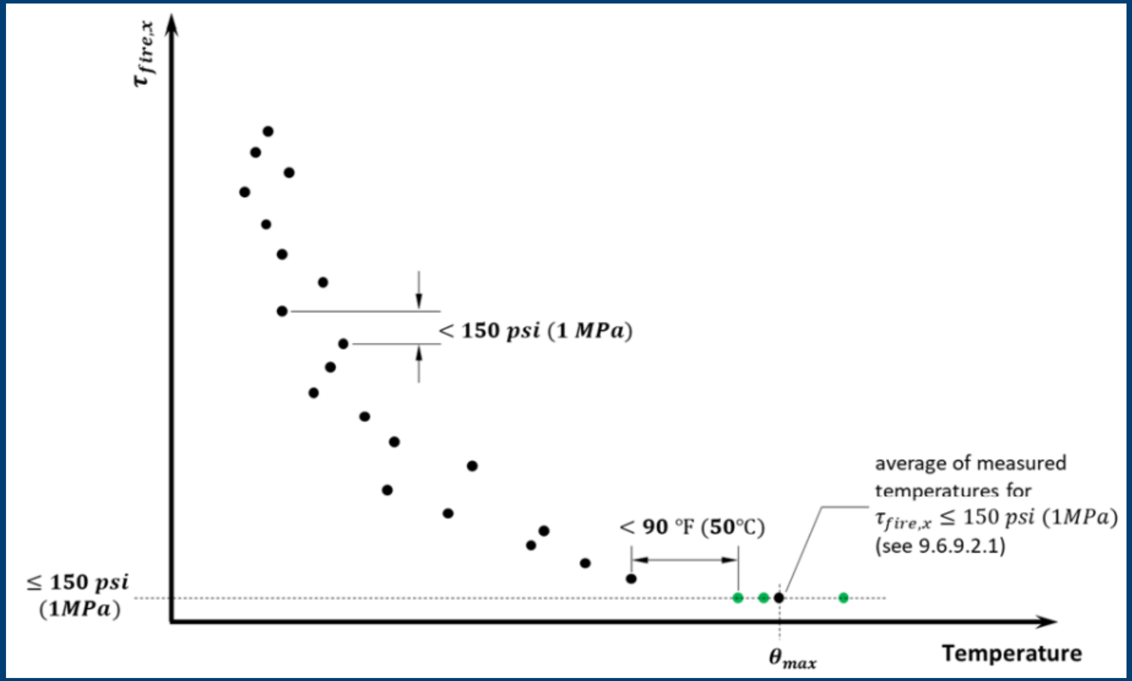
III. Design Concept

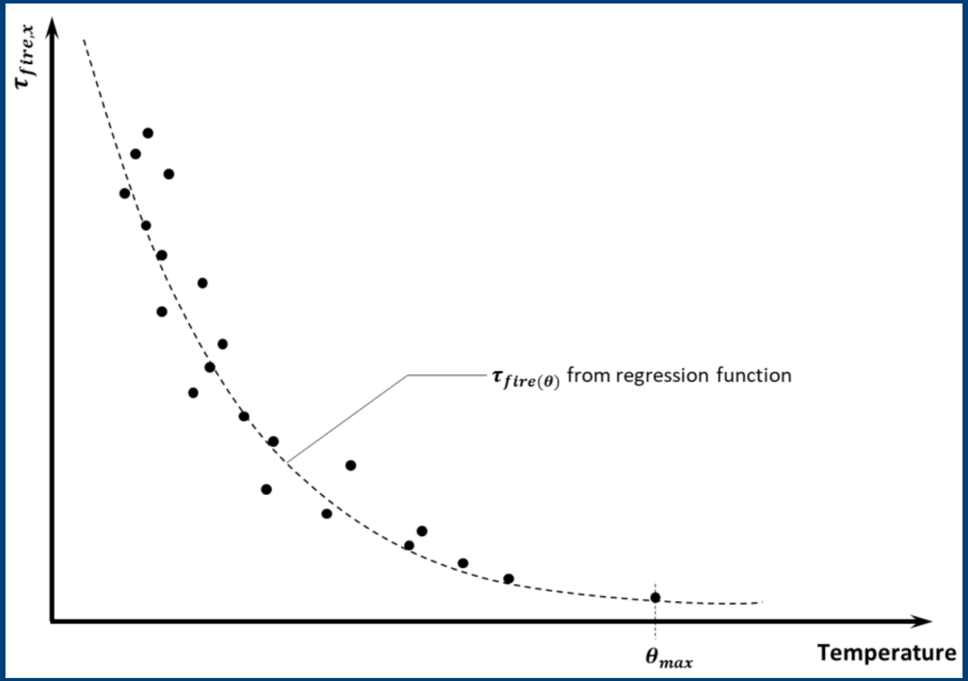

N_{sust}
5
3
10 mm
TC1
4
120 mm
θ
> 200 mm
TC2
1
2
150 mm


Device Frame
Steel support
Heating device
Specimen
Connection device
Jack
Displacement
Load


four
Cylindre béton
cage
rebar
bâti
vérin

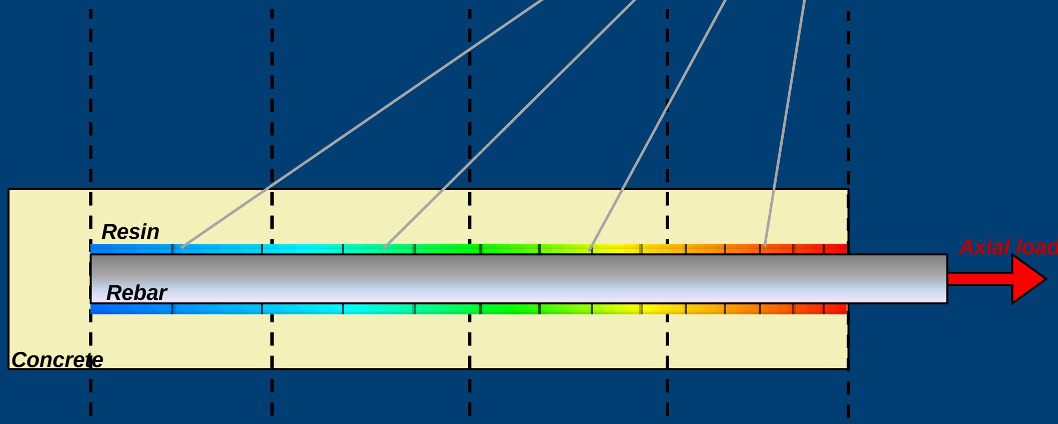
Position of the data points for testing



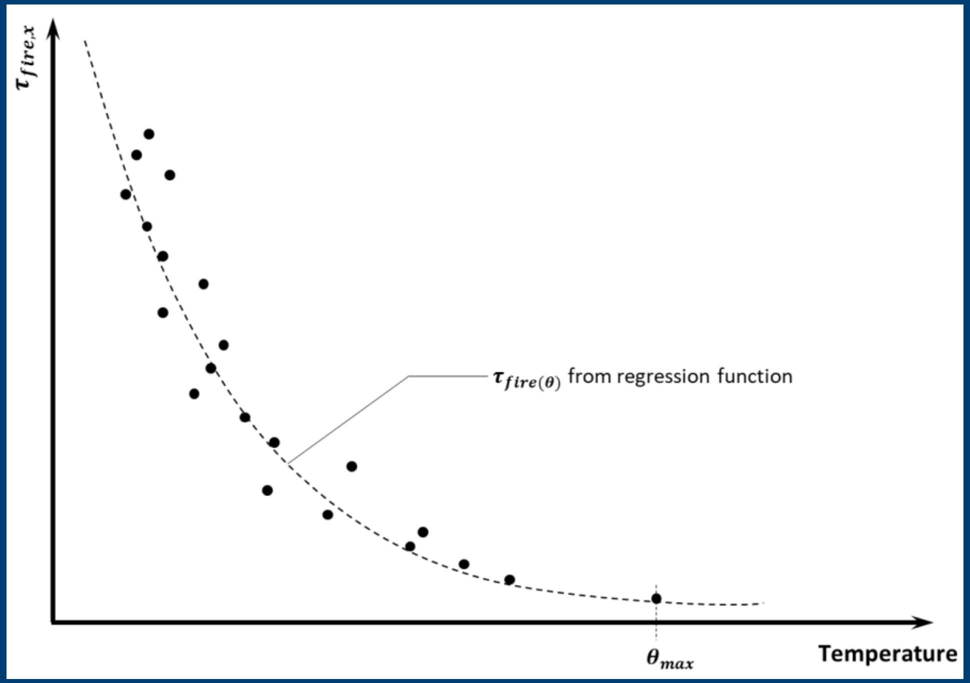


Determination of the load-bearing capacity $N_{Rd,fire}$ at a given time during the fire

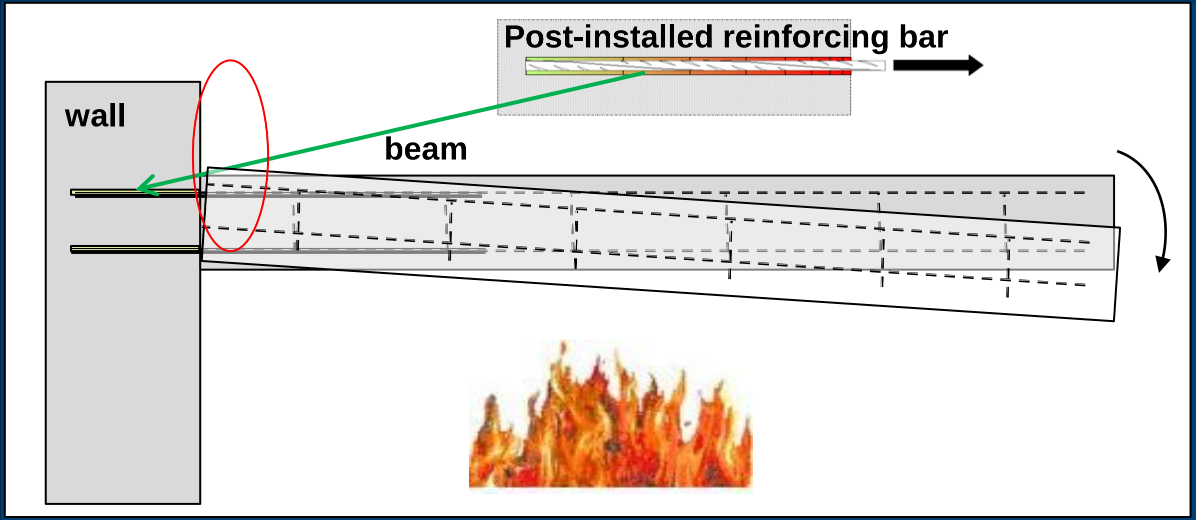
$$N_{Rd,fire} = \pi \cdot d \cdot \int_0^{l_v} f_{bd,fire} \cdot k(\theta(x)) \cdot dx$$

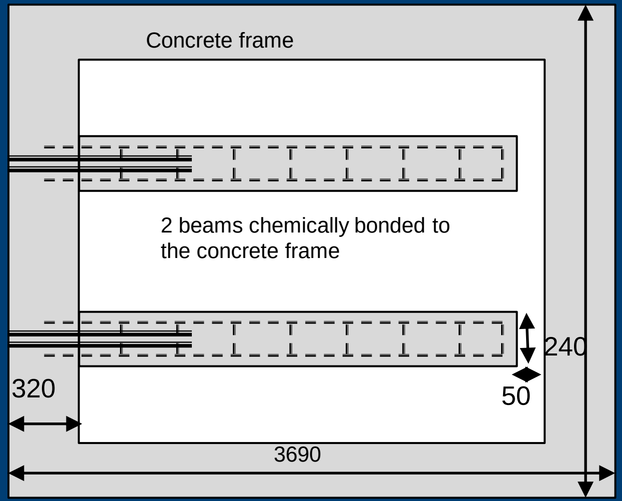


$k(\theta)$

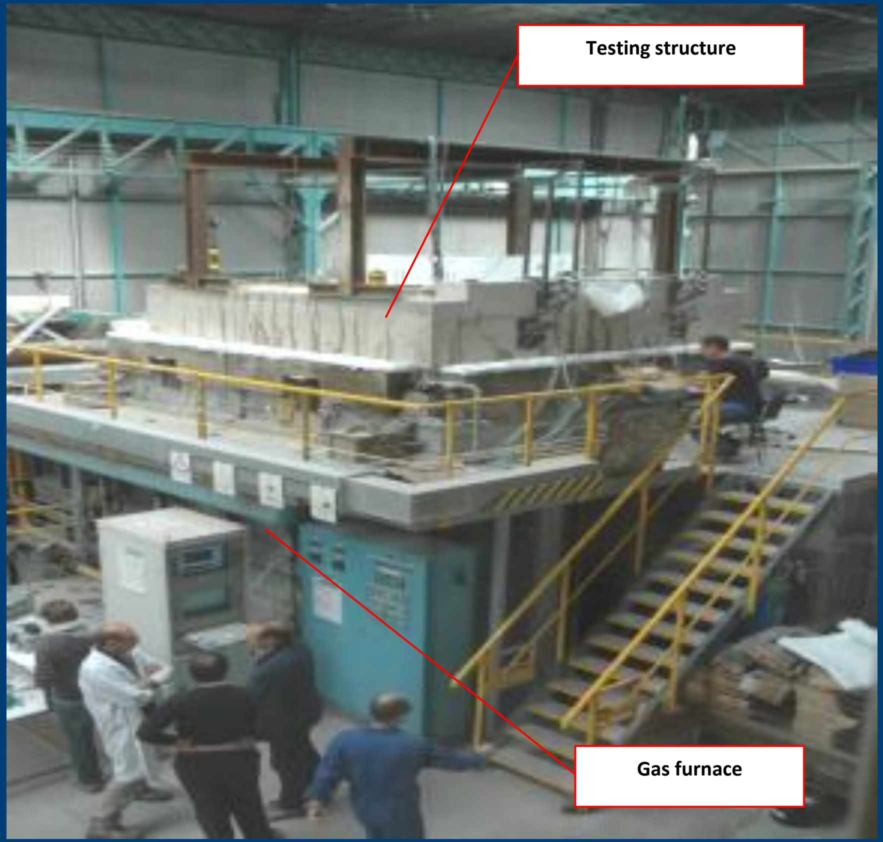


Full Scale Validation Test: Beam-Wall connection

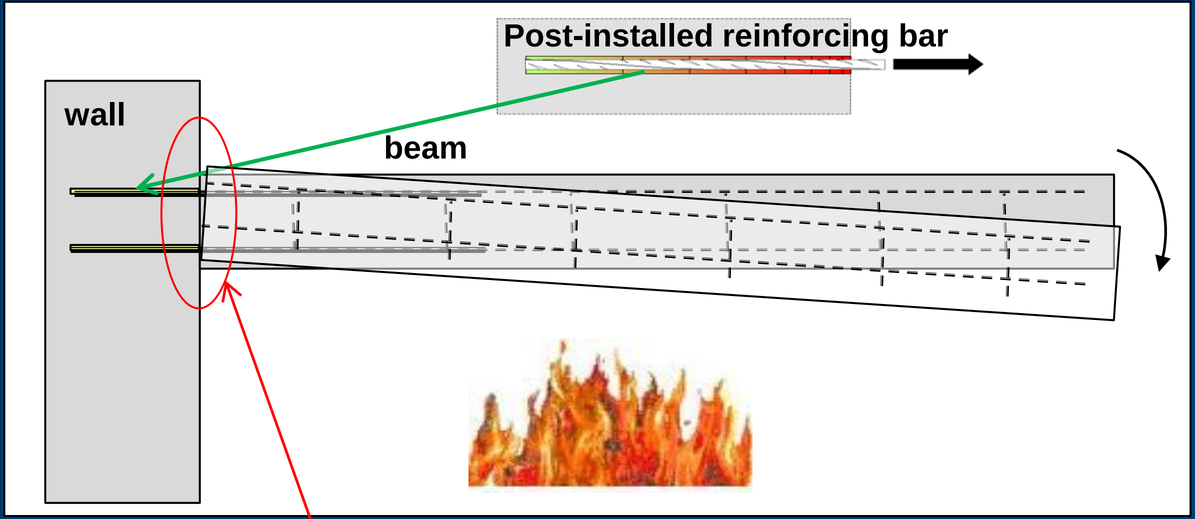


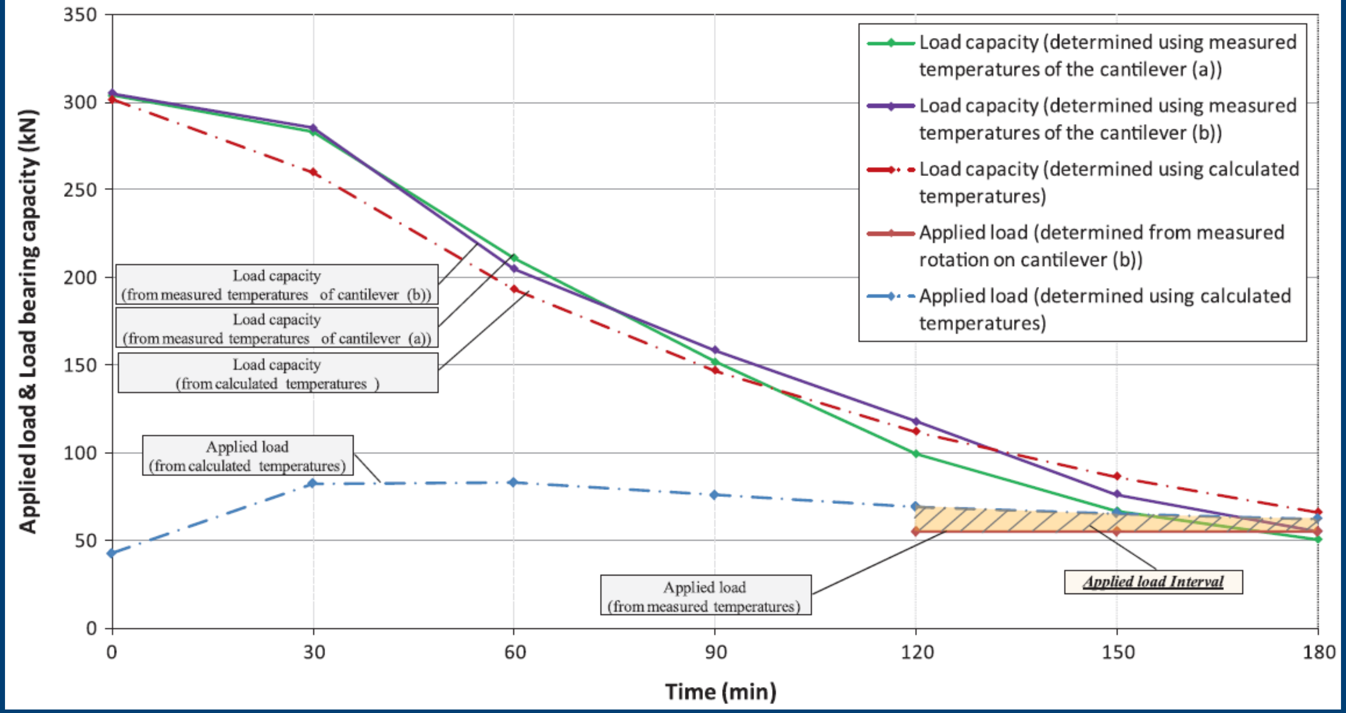


Pinoteau et al. Prediction of failure of a cantilever-wall connection using post-installed rebars under thermal loading. Eng Struct 2013;56:1607-19

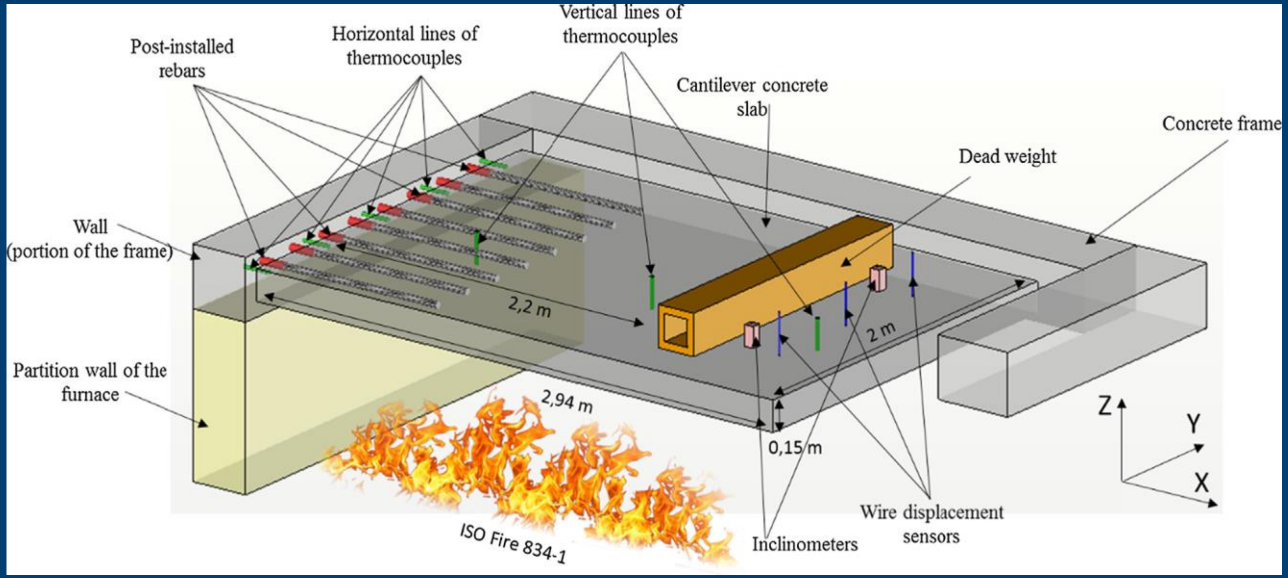


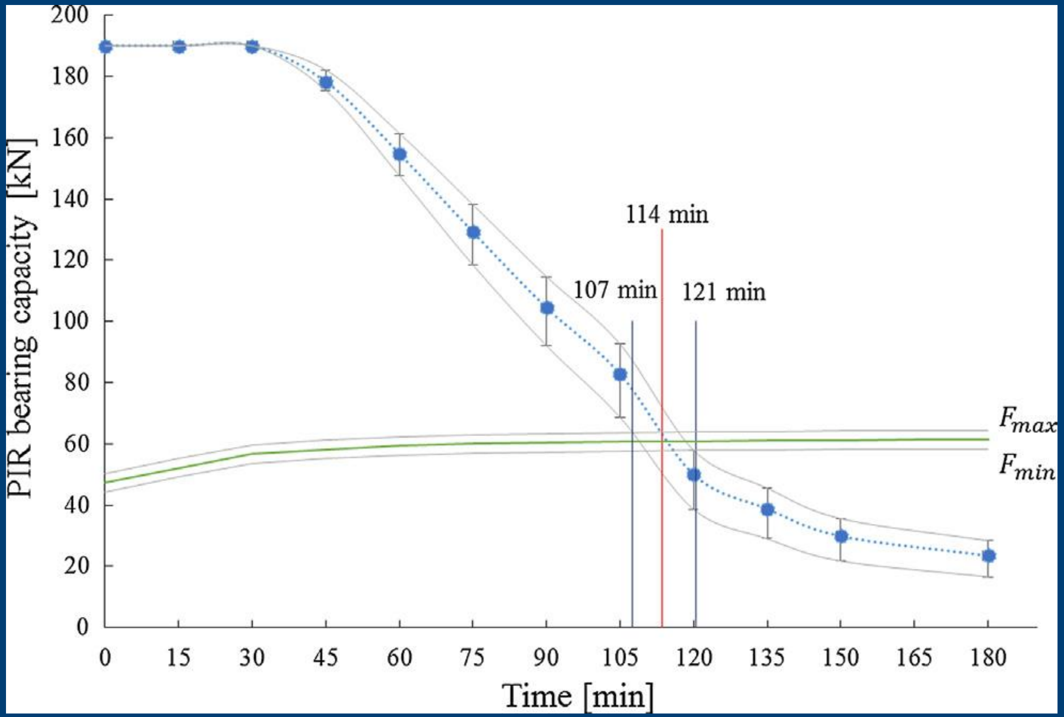
Full Scale Validation Test: Beam-Wall connection





Full Scale Validation Test: Slab-Wall connection



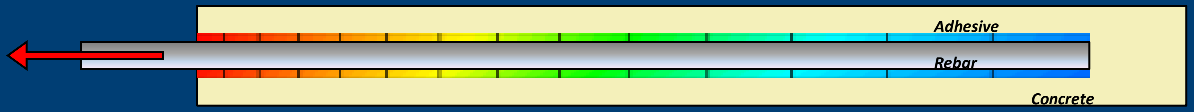


Observed collapse: **118 minutes**
Theoretical predication: **107 – 121 minutes**

Lahouar et al. Fire design of post-installed bonded rebars: Full-scale validation test on 2.94 × 2 × 0.15 m^3 concrete slab subjected to ISO 834-1 fire. Eng Struct 2018;174:81-94

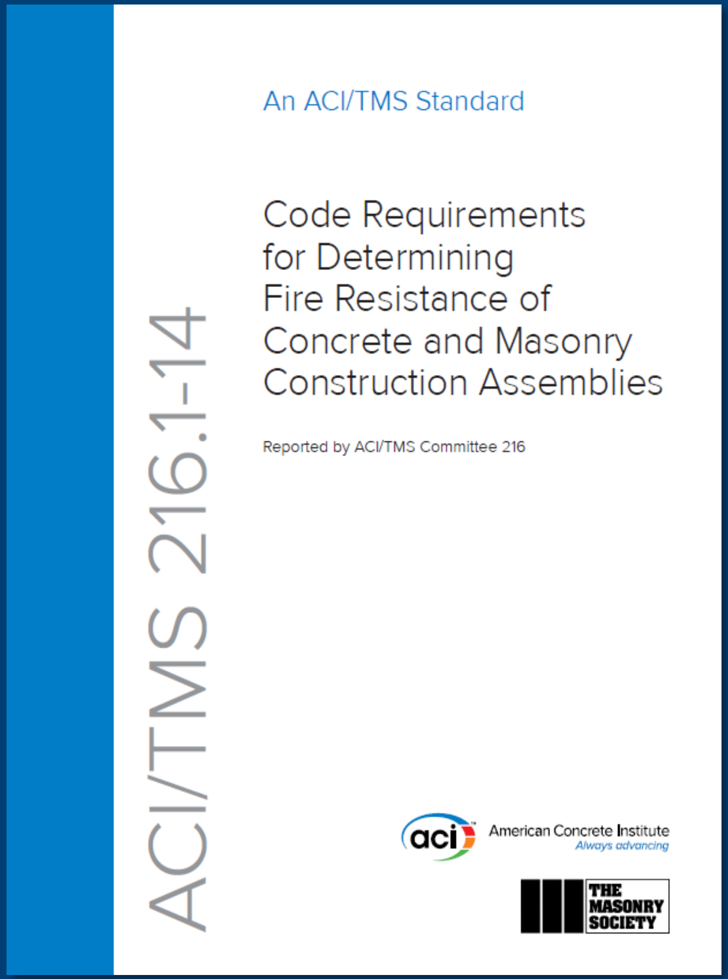
Illustration of ACI 216.1 design concept for post-installed reinforcing bars under fire conditions

Design "load" set equal to bar yield



Capacity determined by adding segments of adhesive based on their relative contributions to temperature. Length is continually increased until the additive capacity of the segments equals the bar yield.

Each segment cannot contribute more capacity than the equivalent bond stress calculated using "cold" development length.



Design methodology fully based on Pinoteau (2011), but phrased in terms of development length.

$$f_y \cdot A_b = \pi \cdot d_a \cdot \tau_{equiv} \cdot \int_0^{\ell_{d,fi}} k_{fi(\theta(x))}\, dx$$

Bar yield

"Cold" unit strength using development length equation

Sum of reduction factors due to temperature along bond

where $\tau_{equiv} = \frac{f_y \cdot A_b}{\pi \cdot d_b \cdot \ell_d}$

"Cold" development length from ACI 318

1. Determine "cold" (no fire conditions) development length, ℓ_d, in accordance with ACI 318.

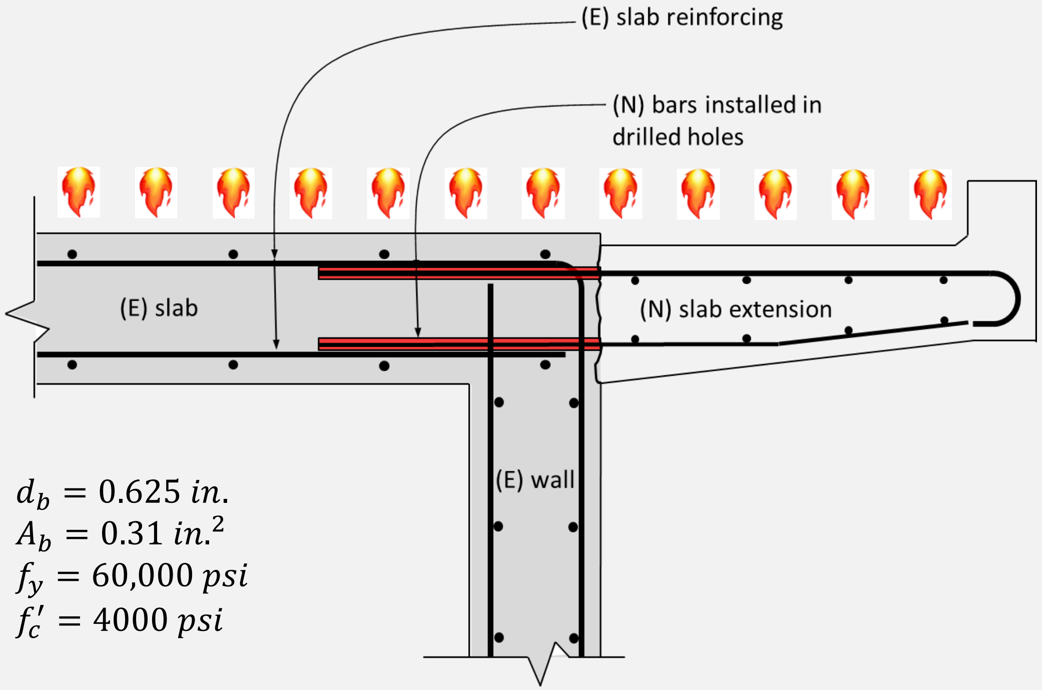
2. Determine equivalent bond stress, τ_{equiv}, by dividing the yield capacity of the bar by the surface area of the cold development length, i.e., $\tau_{equiv} = \frac{f_y \cdot A_b}{\pi \cdot d_b \cdot \ell_d}$

3. Determine temperature profile along bar based on fire rating (e.g., 2 hours) and connection geometry/exposure.

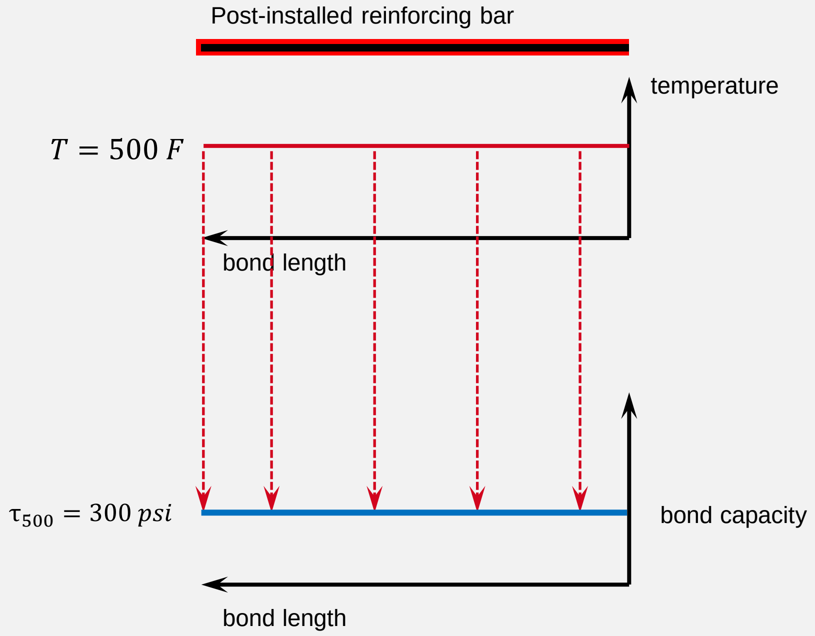
4. Discretize bond line of post-installed reinforcement into segments and determine the cumulative capacity of the segments along the entire length.

5. Add length/segments to the installation until the cumulative capacity equals the yield capacity of the bar. **The final required length is the fire-rated development length.**

Simple case: constant temperature



$d_b = 0.625\ in.$
$A_b = 0.31\ in.^2$
$f_y = 60{,}000\ psi$
$f'_c = 4000\ psi$

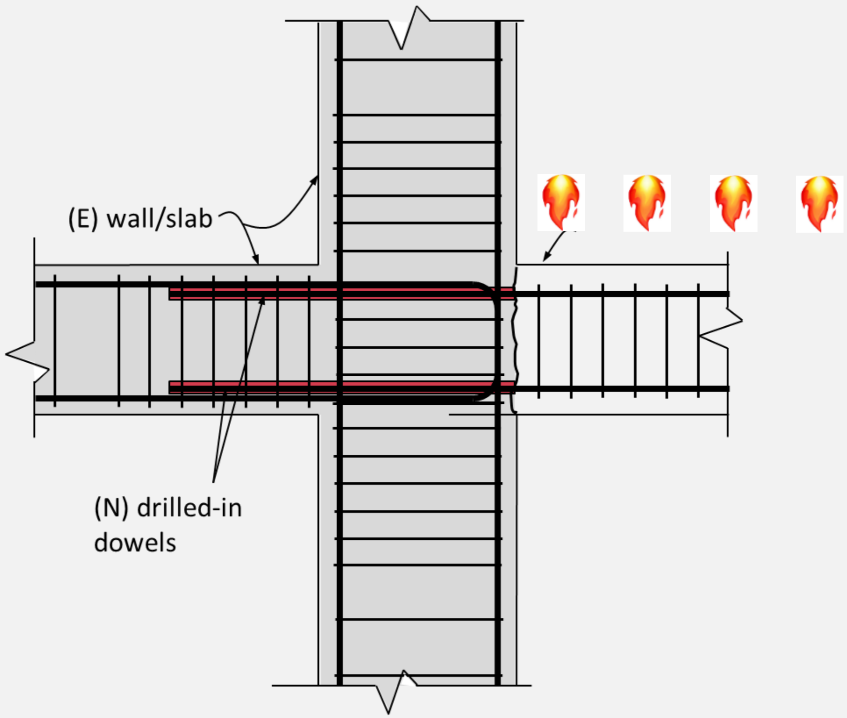


$$\ell_{d,cold} = \left(\frac{3}{40}\frac{60{,}000\ psi}{\sqrt{4000\ psi}}\frac{0.8}{(2.5)}\right) 0.625 = 14.25\text{ in.}$$

$$\tau_{equiv} = \frac{f_y \cdot A_b}{\pi \cdot d_b \cdot \ell_{d,cold}} = 670\text{ psi}$$

$$\ell_{d,hot} = \frac{\tau_{equiv}}{\tau_{500}} \cdot \ell_{d,cold} = \frac{670\ psi}{300\ psi} \cdot 14.25\ in. = \mathbf{31.8\ in.}$$

General case: constant temperature

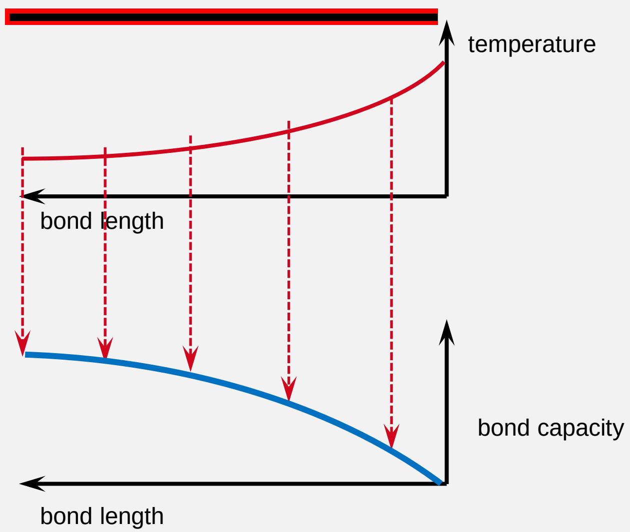


Bond capacity → F_{fi} (lbf); Bar yield → $f_y{*}A_b$ (lbf)

x (in.)	θ (°F)	τ_m (psi)	k_{fi}	F_{fi} (lbf)	$f_y{*}A_b$ (lbf)
0.0	1170.3	0.7	0.0	0	18600
0.4	1038.0	1.9	0.0	1	18600
0.8	897.7	5.1	0.0	2	18600
1.2	763.4	13.5	0.0	6	18600
1.6	643.1	32.3	0.0	16	18600
2.0	539.1	68.4	0.1	41	18600
2.4	450.6	129.5	0.2	94	18600
2.8	376.0	222.1	0.3	194	18600
3.1	313.3	349.2	0.5	366	18600
3.5	273.9	464.1	0.7	636	18600
3.9	243.1	579.8	0.9	995	18600
4.3	217.6	697.1	1.0	1443	18600
4.7	196.0	814.8	1.0	1961	18600
5.1	177.1	933.8	1.0	2479	18600
5.5	160.7	1051.7	1.0	2997	18600
5.9	146.4	1165.9	1.0	3515	18600
6.3	134.1	1274.4	1.0	4033	18600
6.7	123.5	1375.6	1.0	4551	18600
7.1	114.4	1468.4	1.0	5069	18600
7.5	106.8	1552.2	1.0	5586	18600
7.9	100.3	1626.6	1.0	6104	18600
8.3	94.8	1691.9	1.0	6622	18600
8.7	90.3	1748.4	1.0	7140	18600
16.1	71.1	2008.1	1.0	16981	18600
16.5	71.1	2008.6	1.0	17499	18600
16.9	71.1	2008.9	1.0	18017	18600
17.3	71.0	2009.1	1.0	18535	18600
17.7	71.0	2009.3	1.0	19053 >	18600
18.1	71.0	2009.4	[illegible]	[illegible]	[illegible]
18.5	71.0	2009.4	[illegible]	[illegible]	[illegible]

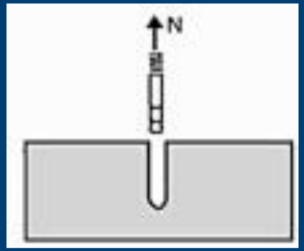
$l_{d,fire}$ at 120 min

$$\pi \cdot d_b \cdot \ell_{seg} \cdot \tau_{equiv} \sum_{i=1}^{n_{req}} k_{fi(\theta_{max}(seg_i))} > f_y \cdot A_b$$

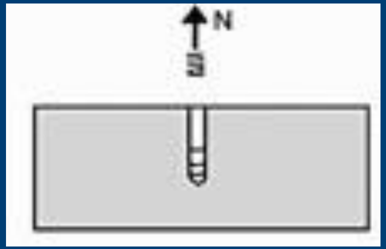


Anchorage

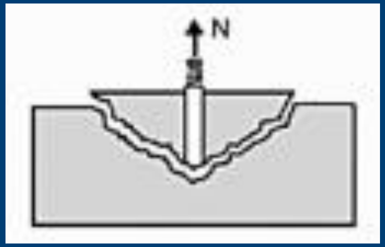
Differences between Anchors & Reinforcing bars:
- Possible direct exposure to fire
- Shorter embedment depths
- Additional failure modes (break-out, pry-out)



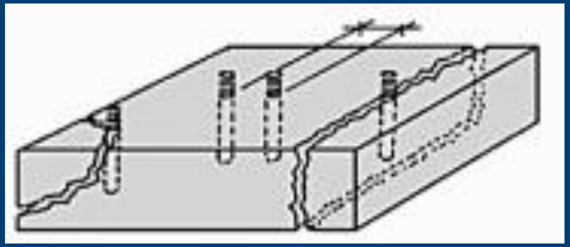
Bond



Steel failure



Concrete cone


Concrete splitting

Conclusion

There is a validated method for predicting failure of post-installed reinforcing bars relying on:

- product evaluation by testing of the bond system
- estimation of temperature fields

A design concept is proposed in accordance with ambient temperature design.

Future work:

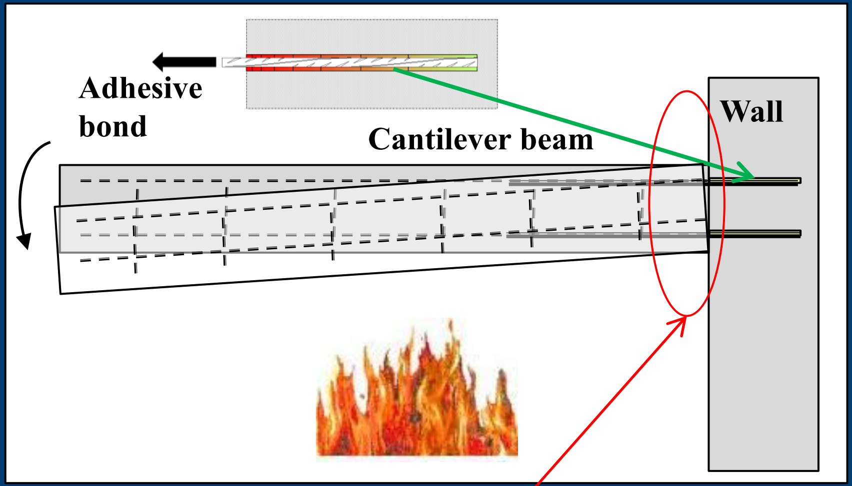
- Propose a design method for bonded anchors in fire

Al-Mansouri PhD Memoire, 2020, Behavior of bonded anchors in concrete under fire

Thank you

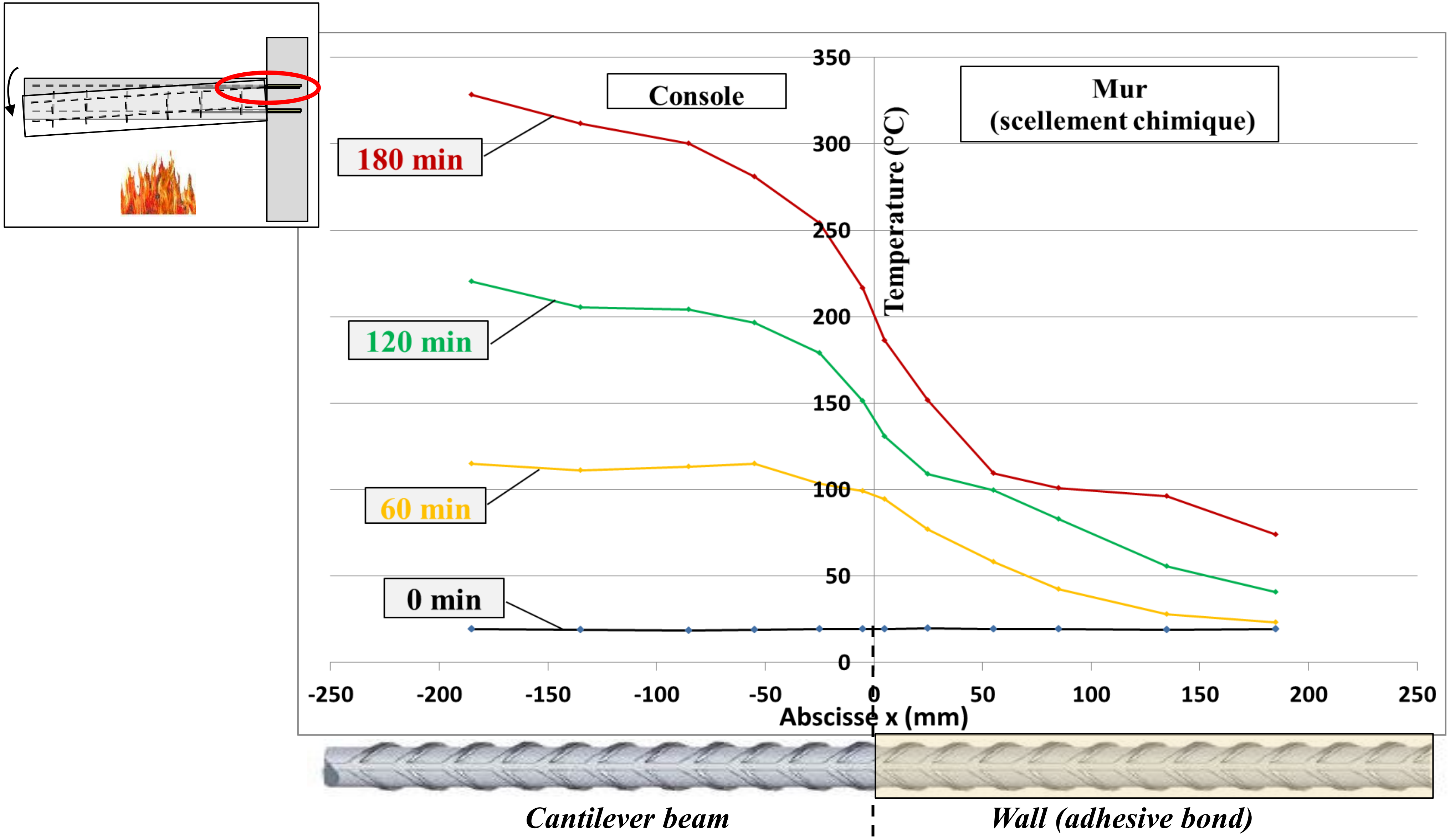
For the most up-to-date information please visit the American Concrete Institute at:
www.concrete.org

ADDITIONAL SLIDES

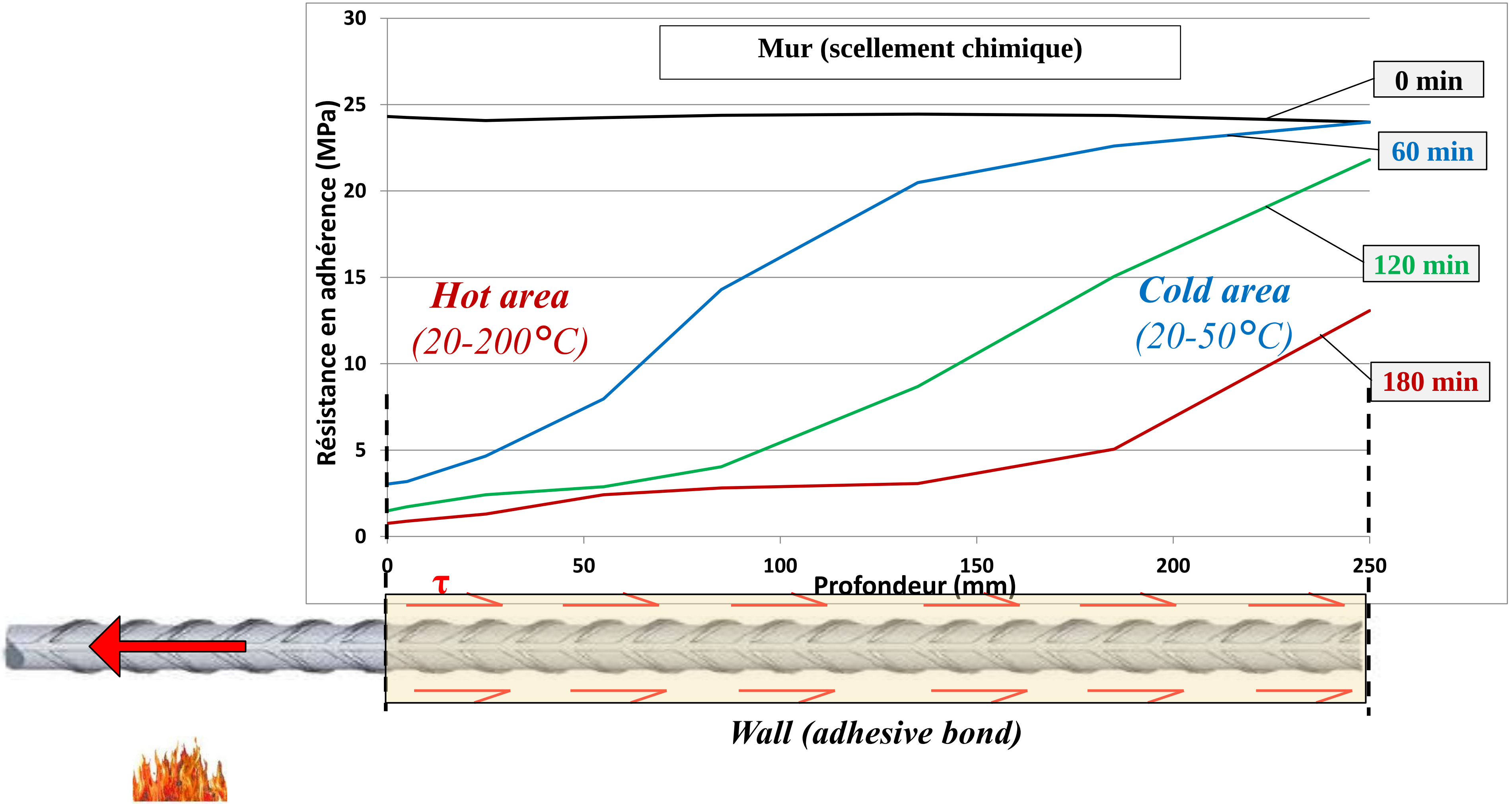

Adhesive
bond
Cantilever beam
Wall

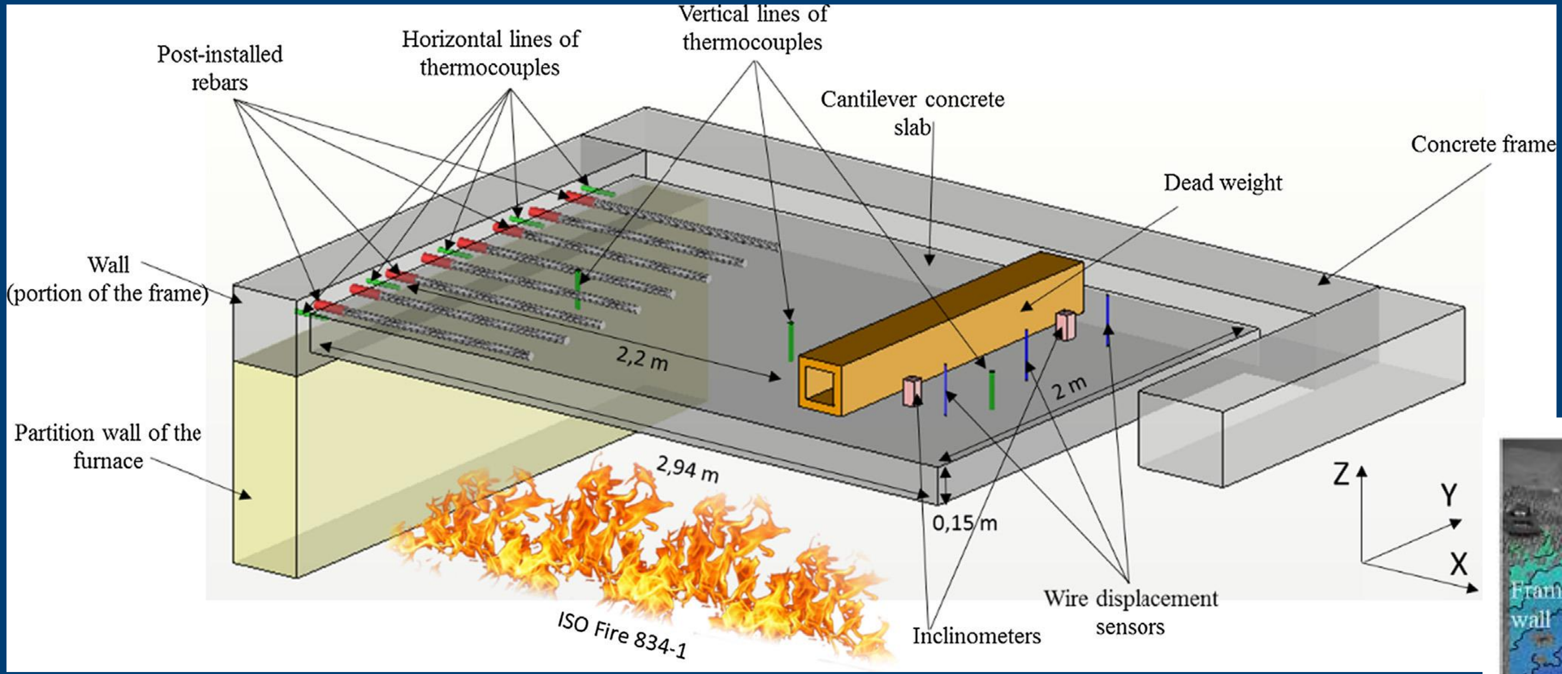

Wall
Rebar
Beam
Photo after cooling

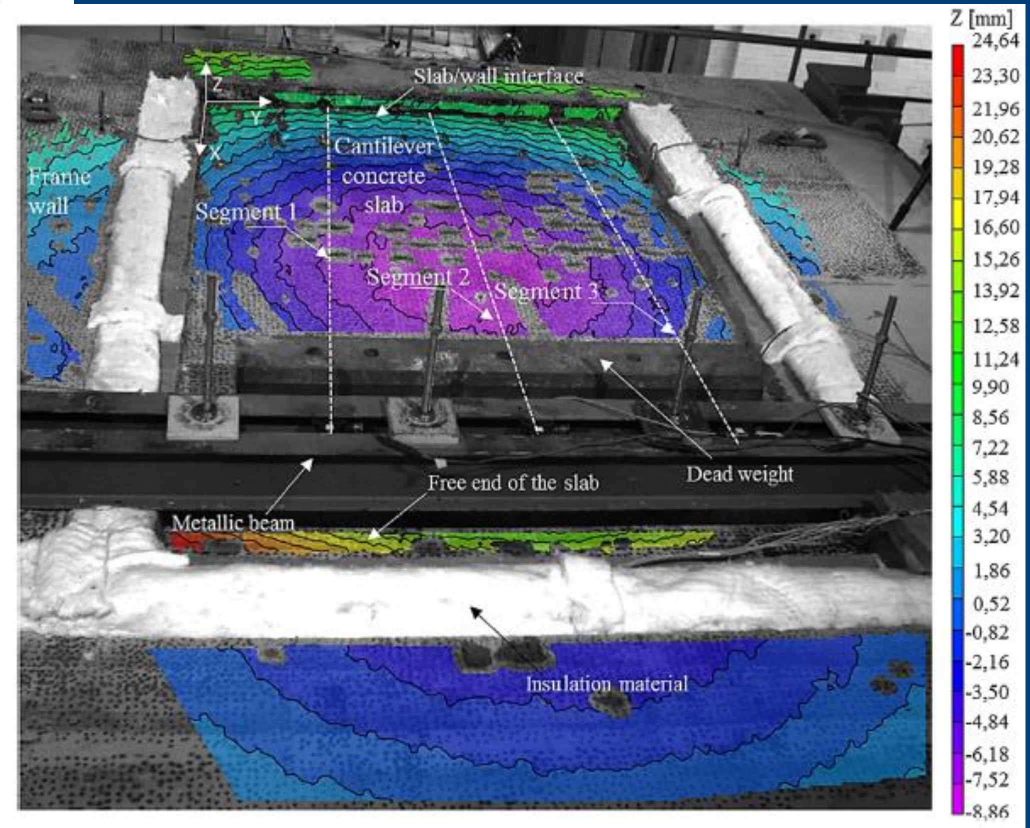
Temperature Profiles



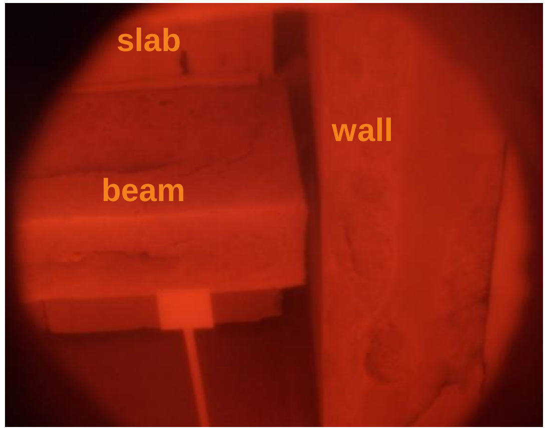
- Theoretical prediction ➔ between 150 and 180 min
- Experimental observation ➔ 178 min for the 1st beam




Vertical lines of thermocouples
Post-installed rebars
Horizontal lines of thermocouples
Cantilever concrete slab
Concrete frame
Dead weight
Wall (portion of the frame)
2,2 m
2 m
Partition wall of the furnace
2,94 m
0,15 m
Z
Y
X
ISO Fire 834-1
Inclinometers
Wire displacement sensors


Z [mm]
24,64
23,30
21,96
20,62
19,28
17,94
16,60
15,26
13,92
12,58
11,24
9,90
8,56
7,22
5,88
4,54
3,20
1,86
0,52
-0,82
-2,16
-3,50
-4,84
-6,18
-7,52
-8,86
Slab/wall interface
Frame wall
Cantilever concrete slab
Segment 1
Segment 2
Segment 3
Free end of the slab
Dead weight
Metallic beam
Insulation material

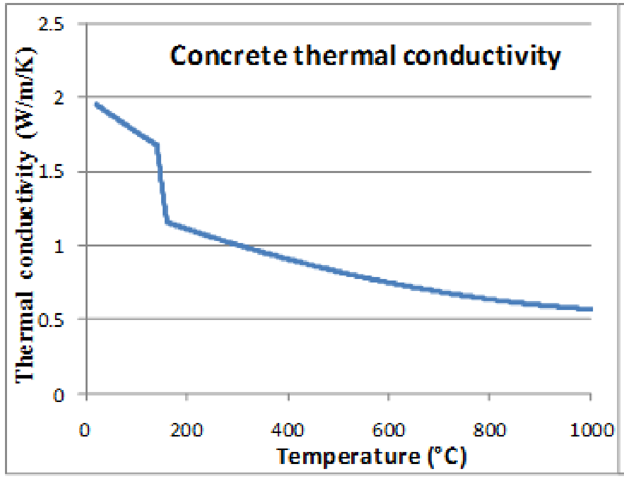
Thermal calculation (EC2 method)

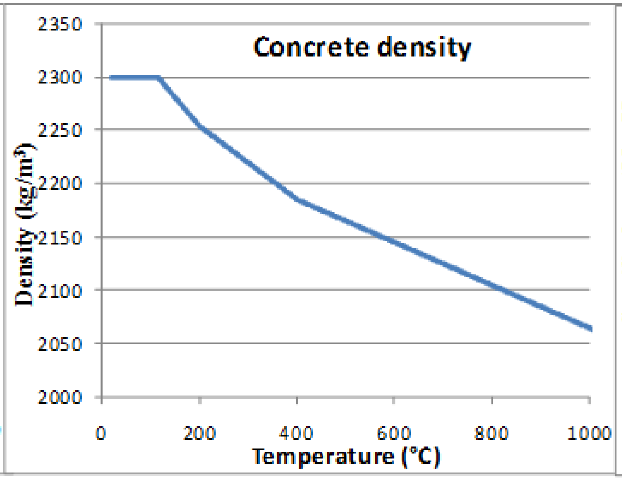


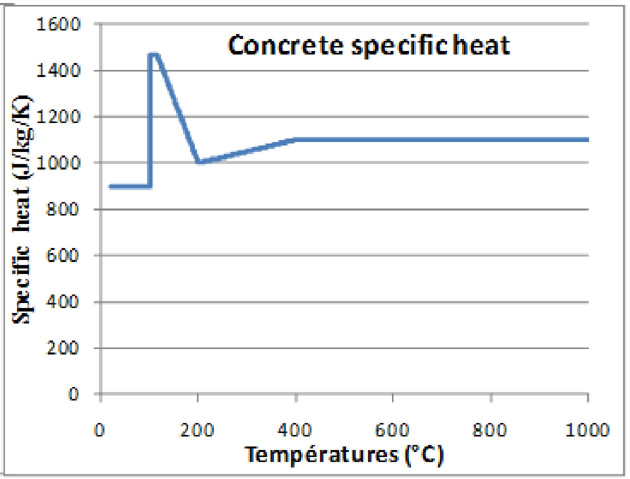
ISO 834-1 time-temperature relationship (EN 1991-1-2, section 3)

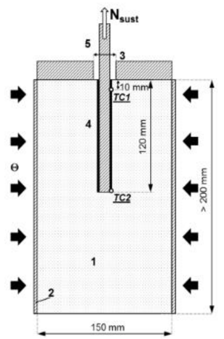
$$\theta_g(t) = \theta_0 + 345.\,log_{10}(8.\,t + 1)$$

- convective flux density: $\varphi_c = h.\,(\theta_g - \theta_s)$ (W/m²),
- radiation flux density: $\varphi_c = \varepsilon.\,\sigma.\left(\theta_g^4 - \theta_s^4\right)$ (W/m²).



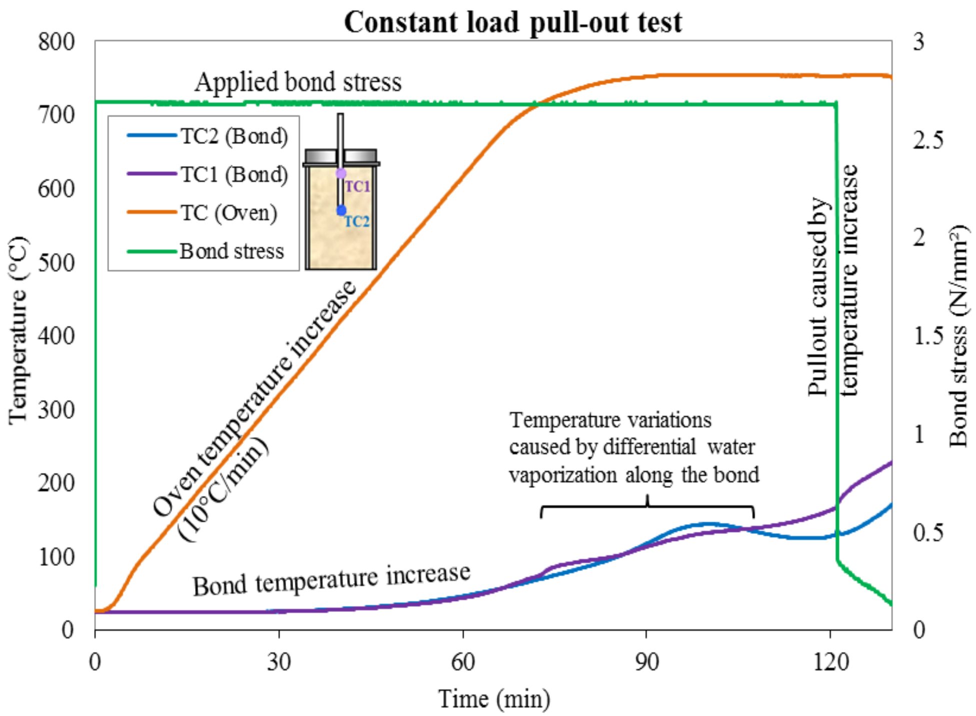




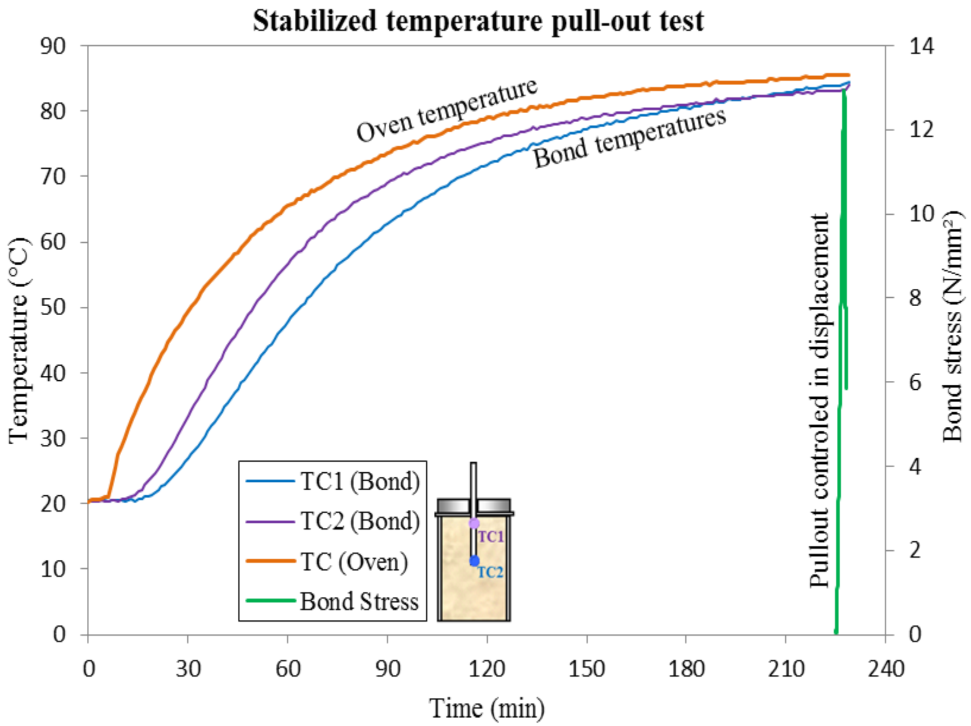


Test sample: concrete cylinder with a bonded rebar (d=12 mm, lv=120 mm)

① Constant load, temperature increase



② Stabilized temperature, Pullout



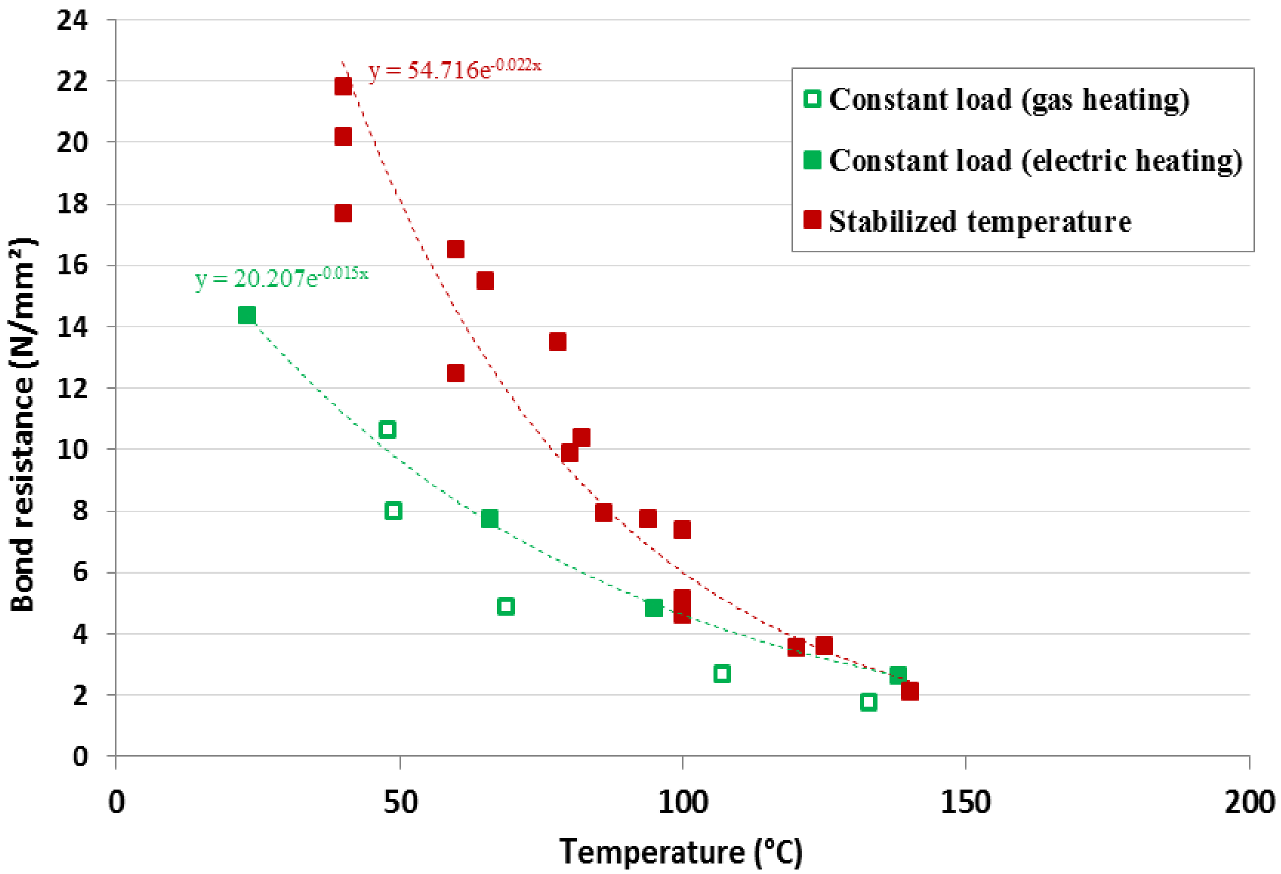
① **Constant load**

Sustained load: ↘ resistance

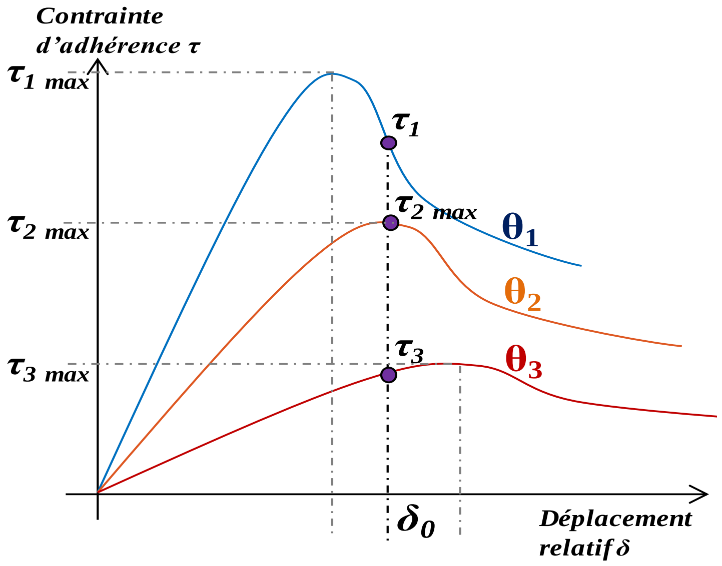
Moisture diffusion:↘ resistance

② **Stabilized temperature**

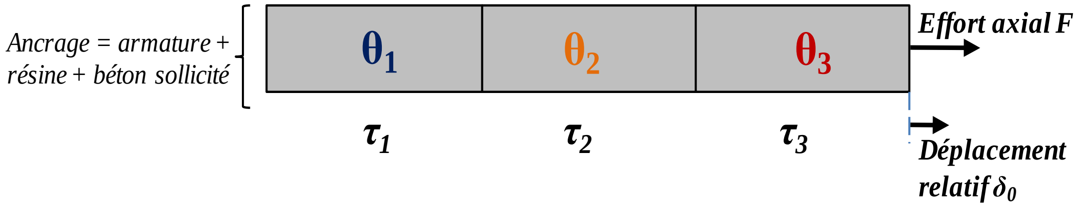
Longer test (post cure): ↗ resistance



Choice for evaluation = **Constant load** (representative and conservative)

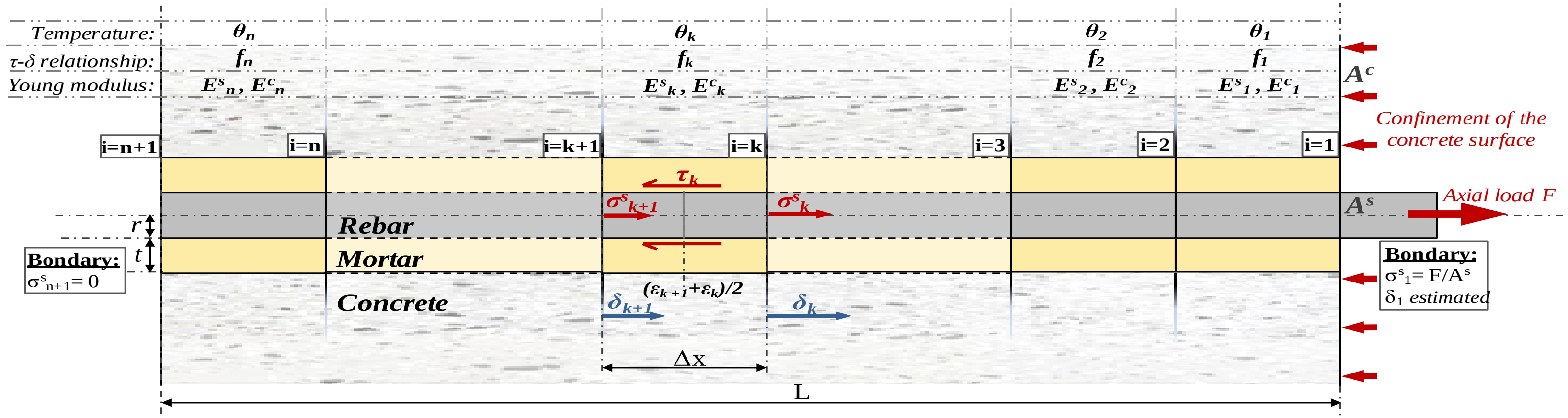


Take slip into account

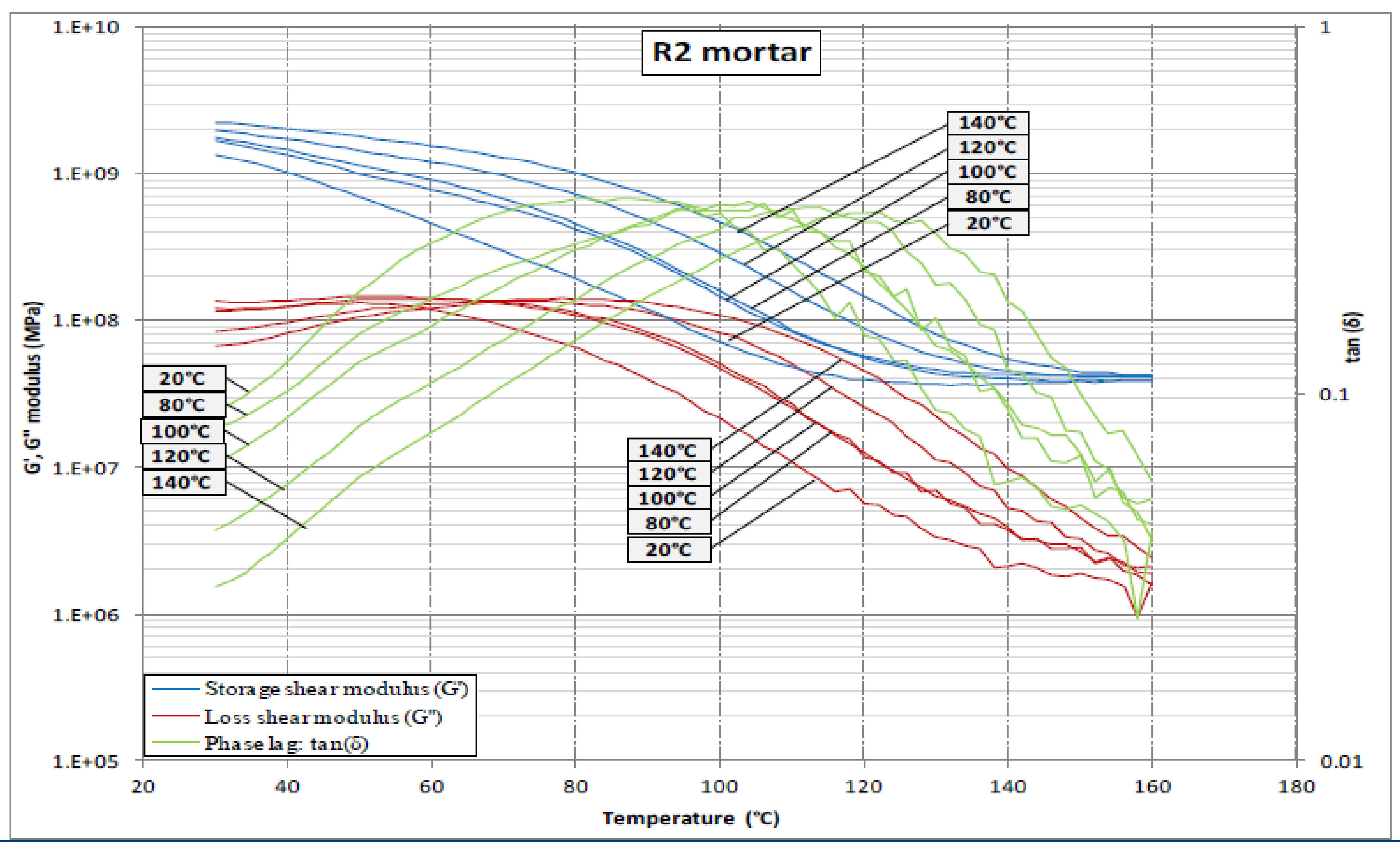


Shear Lag bond model

$$\frac{d^2\delta(x)}{dx^2} = \frac{2}{r}\cdot\left[\frac{1}{E^s(\theta(x))} + \frac{A^s}{A^c}\cdot\frac{1}{E^c(\theta(x))}\right]\cdot f(\delta(x),\theta(x))$$

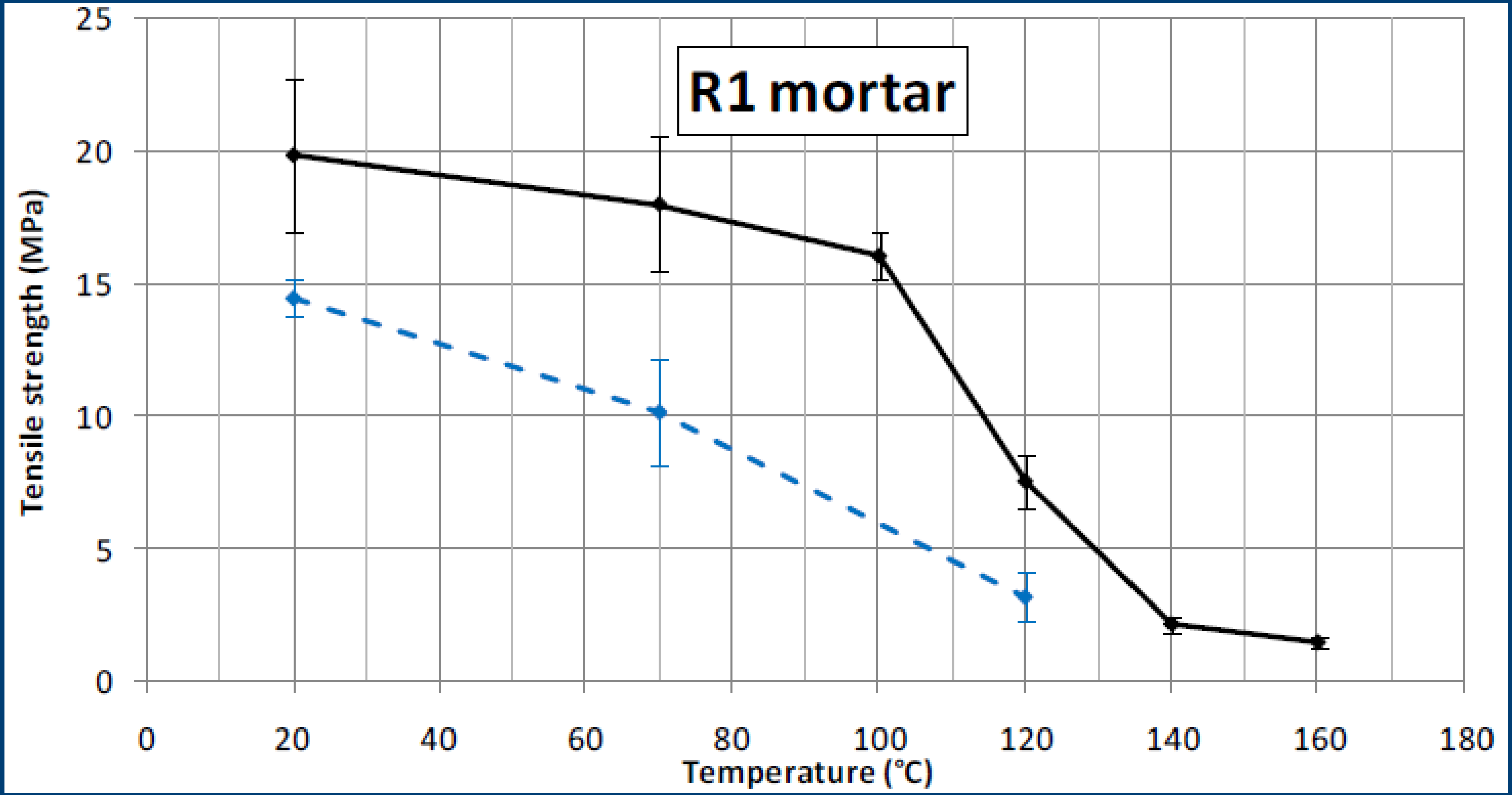


DMTA tests



R2 mortar
1.E+10
1.E+09
1.E+08
1.E+07
1.E+06
1.E+05
G', G" modulus (MPa)
1
0.1
0.01
tan (δ)
20
40
60
80
100
120
140
160
180
Temperature (°C)
140°C
120°C
100°C
80°C
20°C
20°C
80°C
100°C
120°C
140°C
140°C
120°C
100°C
80°C
20°C
Storage shear modulus (G')
Loss shear modulus (G")
Phase lag: tan(δ)

Effect of water on the tensile strength



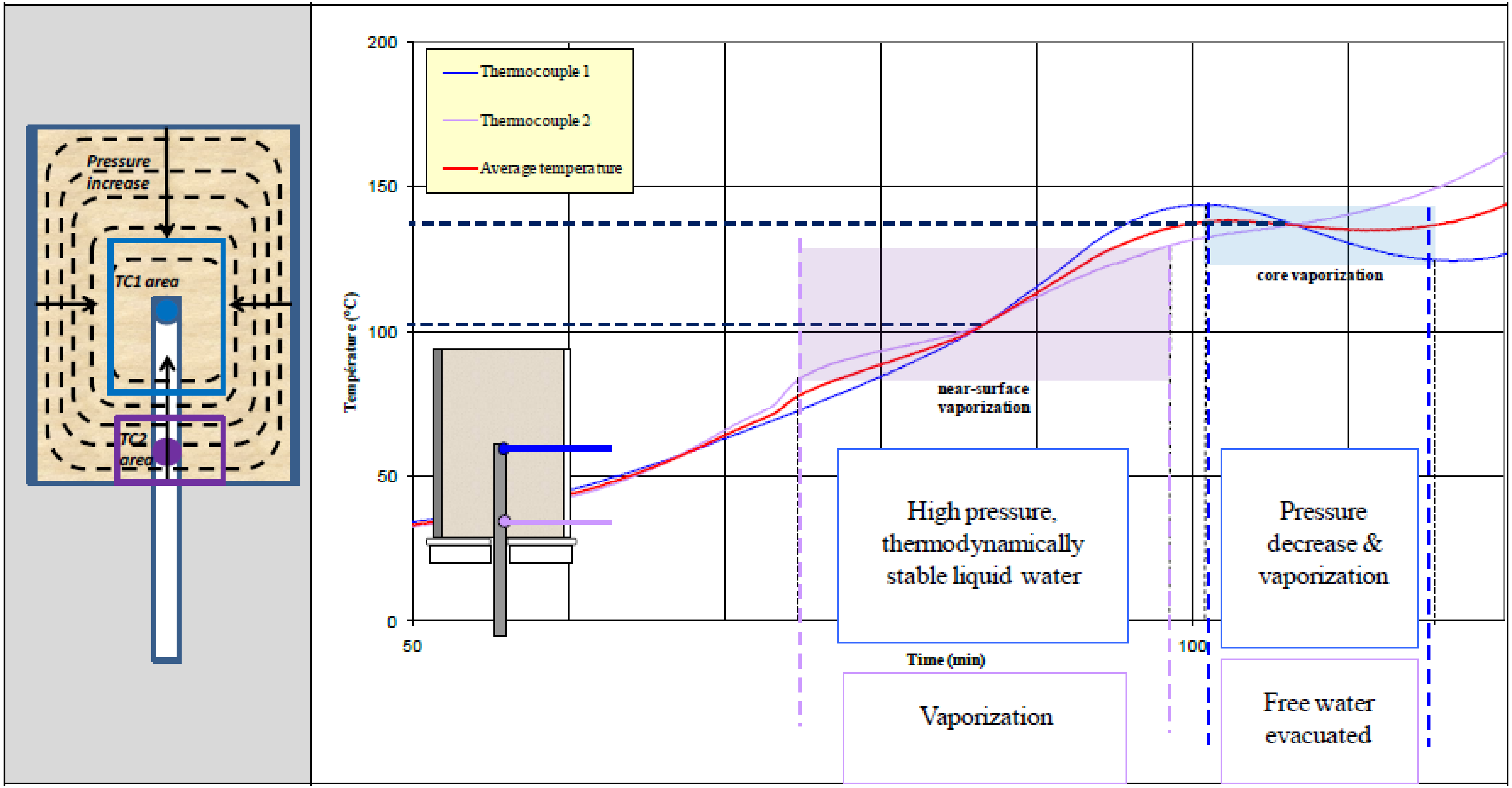

Pressure increase
TC1 area
TC2 area
Thermocouple 1
Thermocouple 2
Average temperature
200
150
100
50
0
Température (°C)
50
100
Time (min)
near-surface vaporization
core vaporization
High pressure, thermodynamically stable liquid water
Pressure decrease & vaporization
Vaporization
Free water evacuated

TABLE 722.2.3(1)
COVER THICKNESS FOR REINFORCED CONCRETE FLOOR OR ROOF SLABS (inches)

CONCRETE AGGREGATE TYPE	FIRE-RESISTANCE RATING (hours)									
	Restrained					Unrestrained				
	1	1 1/2	2	3	4	1	1 1/2	2	3	4
Siliceous	3/4	3/4	3/4	3/4	3/4	3/4	3/4	1	1 1/4	1 5/8
Carbonate	3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4	1 1/4	1 1/4
Sand-lightweight or lightweight	3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4	1 1/4	1 1/4

For SI: 1 inch = 25.4 mm.

TABLE 722.2.3(2)
COVER THICKNESS FOR PRESTRESSED CONCRETE FLOOR OR ROOF SLABS (inches)

CONCRETE AGGREGATE TYPE	FIRE-RESISTANCE RATING (hours)									
	Restrained					Unrestrained				
	1	1 1/2	2	3	4	1	1 1/2	2	3	4
Siliceous	3/4	3/4	3/4	3/4	3/4	1 1/8	1 1/2	1 3/4	2 3/8	2 3/4
Carbonate	3/4	3/4	3/4	3/4	3/4	1	1 3/8	1 5/8	2 1/8	2 1/4
Sand-lightweight or lightweight	3/4	3/4	3/4	3/4	3/4	1	1 3/8	1 1/2	2	2 1/4

For SI: 1 inch = 25.4 mm.

- *Pinoteau et al. (2011). Effect of heating rate on bond failure of rebars into concrete using polymer adhesives to simulate exposure to fire, International Journal of Adhesion & Adhesives 31 (2011) 851-861*
- *Pinoteau et al. (2011). Post-installed rebars in concrete at high temperature, fib Symposium, Prague 2011*
- *Pinoteau et al. (2013). Prediction of failure of a cantilever–wall connection using post-installed rebars under thermal loading, Engineering Structures 56 (2013) 1607-1619*
- *Lahouar et al. (2017). Chemically Bonded Post-Installed Steel Rebars in a Full-Scale Slab-Wall Connection Subjected to the Standard Fire (ISO 834-1), Connections between Steel and Concrete, Stuttgart, Germany 2017*
- *Lahouar et al. (2017). Mechanical behavior of adhesive anchors under high temperature exposure: Experimental investigation, International Journal of Adhesion & Adhesives 78 (2017) 200-211*
- *Lahouar et al. (2017). Fire Behaviour of Post-Installed Steel Rebars: Full-Scale Experimentation on a Cantilever Concrete Slab, 2nd International Fire Safety Symposium Naples, Italy, June 7-9, 2017*
- *Lahouar et al. (2018). A nonlinear shear-lag model applied to chemical anchors subjected to a temperature distribution, Journal of Adhesion & Adhesives 84 (2018) 438-450*
- *Lahouar et al. (2018). Fire design of post-installed bonded rebars: Full-scale validation test on a 2.94 × 2 × 0.15 m3 concrete slab subjected to ISO 834-1 fire, Engineering Structures 174 (2018) 81-94*
- *Lahouar et al. (2019). Prediction of Failure Time of Post-Installed Rebars at High Temperature Using a Non-Linear Shear Shear-Lag Model, International Fire Safety Symposium, Ottawa 2019*
- *Al-Mansouri et al. (2019). Experimental and Numerical Investigation of Factors Influencing Thermal Distribution and Load-Bearing Capacity of Bonded Anchors Under Fire, CONFAB 2019*
- *Al-Mansouri et al. (2019). Influence of testing conditions on thermal distribution and resulting load-bearing capacity of bonded anchors under fire, Engineering Structures 192 (2019) 190-204*
- *Al-Mansouri et al. (2019). Influence of Pull-out fire test conditions on the thermal distribution and the prediction of load-bearing capacity of bonded anchors, International Fire Safety Symposium, Ottawa 2019*
- *Al-Mansouri et al. (2020). Numerical investigation of parameters influencing fire evaluation tests of chemically bonded anchors in uncracked concrete*
- *PhD Thesis 2013: Pinoteau, Behavior in Fire of Post-Installed Rebars in Concrete, University Lille I*
- *PhD Thesis 2017: Lahouar, Behavior in Fire of Fasteners in Timber and Concrete, University Paris-Est*
- *PhD Thesis 2020: Al-Mansouri, Behavior of bonded anchors in concrete under fire. Civil Engineering. Ecole nationale supérieure Mines-Télécom Lille Douai, 2020.*