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Fire resistance of hollowcore slabs

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IPHA / Consolis

Organized by IPHA
INTERNATIONAL PRESTRESSED HOLLOWCORE ASSOCIATION

in cooperation with
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CONTENTS

1. INTRODUCTION

Fire resistance of concrete and steel

MICRO

- non-combustible materials (Euroclass A1 - EN 13501-1)

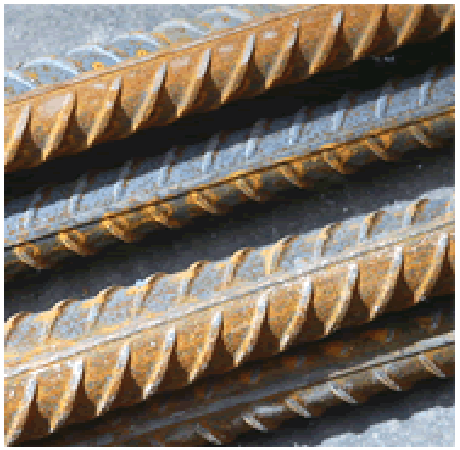
Both:

- Do not burn and do not increase the fire load
- leave no dripping molten material that will spread the fire further
- do not produce smoke or toxic gases

But:

- Concrete insulates heat
- Steel conducts heat

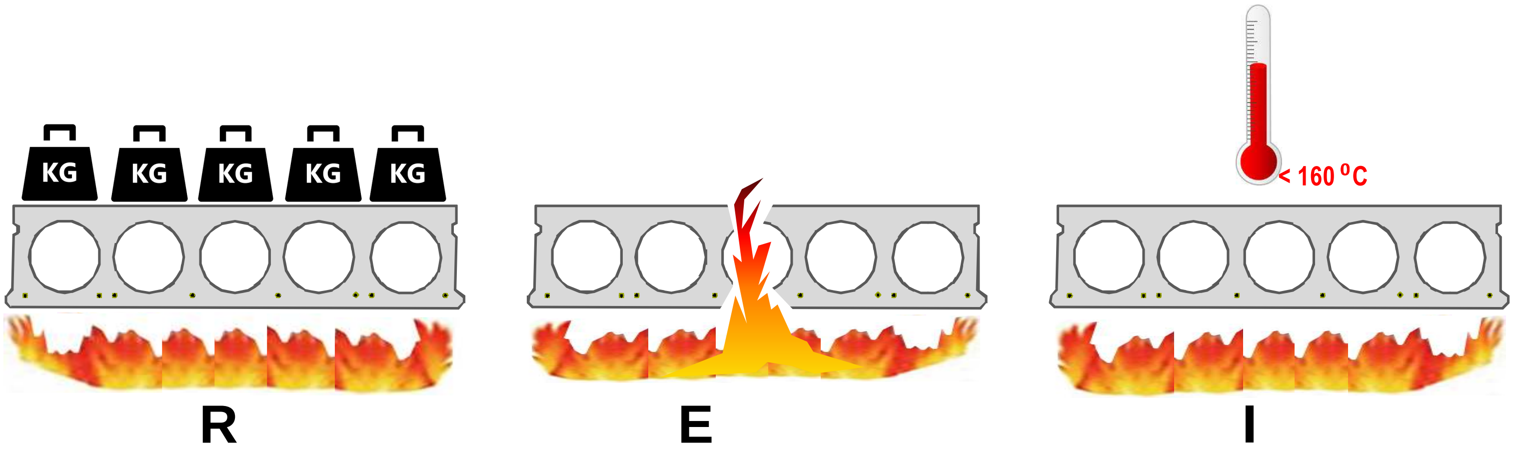





Fire resistance of an element

MESO

- The fire resistance of a building element under the standard ISO 834 fire regime is normally indicated in minutes i.e. 60 minutes
- During this time the following criteria need to be satisfied:
  - **R** : **Load bearing capacity** - Time that the relevant structural element is able to carry the current load in a normal fire development phase
  - **E** : **Integrity** - Time that the structural element retains its integrity against flames or hot gases in a standard fire.
  - **I** : **Insulation** - Time it takes to produce an increase in temperature of 140 ^{0}C on the cold side of the structural element (< 160 ^{0}C) .



Fire resistance of a building

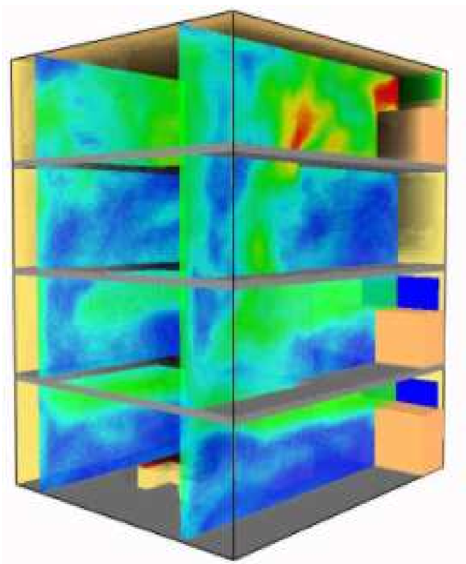
MACRO

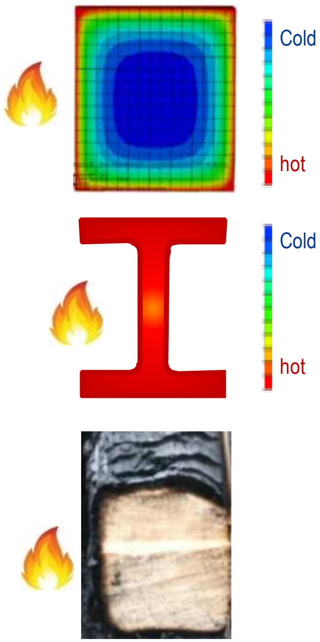
- Fires in buildings are rare and random events
- The fire resistance of a building exposed to fire is a very complex phenomenon:
  - size of the building
  - intensity and extent of the fire
  - location of the fire in the structure
  - structural lay-out and components

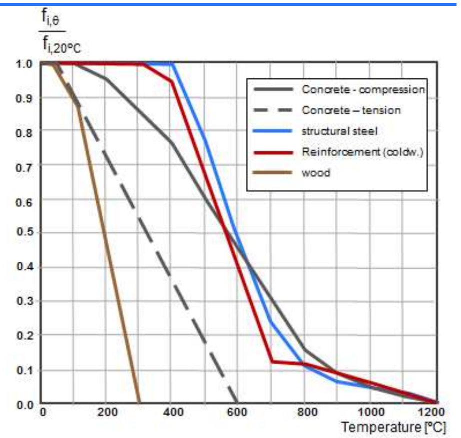
- Passive fire protection by compartmentation
  - prevents the rapid fire spread of fire that could trap occupants
  - Restricts the overall chance of fires growing and creating a danger to occupants, rescue services, and people in the vicinity of the building.
  - Limits the damage caused to a building and its contents

Holistic view on fire resistance

MACRO	MESO	MICRO
structure performance structure	elements behaviour under fire	materials models







Material	Conductivity [W/mK]
Structural steel	50
Reinforcement	50
Stainless steel	15
concrete	1.8
water	0.6
wood	0.14
air	0.026

fire safety engineering	**R** E I	A1 A2 B C D E F
performance-based approach	*prescriptive-based approach*	

2. FIRE TESTS ON HOLLOWCORES

Fire resistance of hollow core slabs

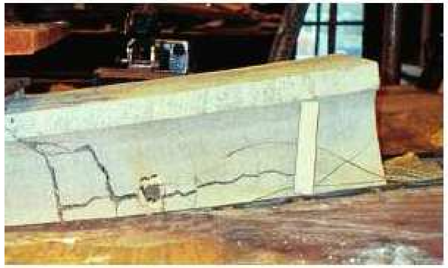
- Since 1966 a total of 162 fire test results have been gathered on pre-stressed hollow core slabs in Europe

Fig 1. VTT-PAL 2892-71 [1971]

Fig 2. RUG 9157 [1999]

Fig 5. SPTRI Peikko [2009]

Fig 6. BRE test 1 [2007]



P260S11 [2001]

Fig 4. SPTRI P502015 [2005]

SOURCE: Holcofire

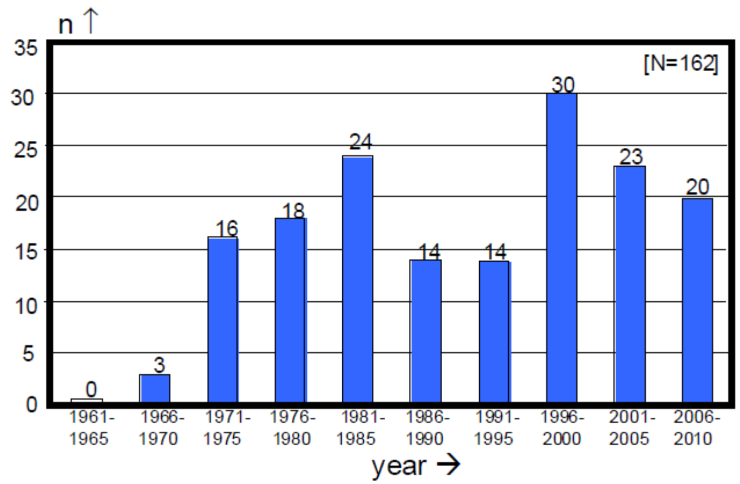
Holcofire project 2010-2013

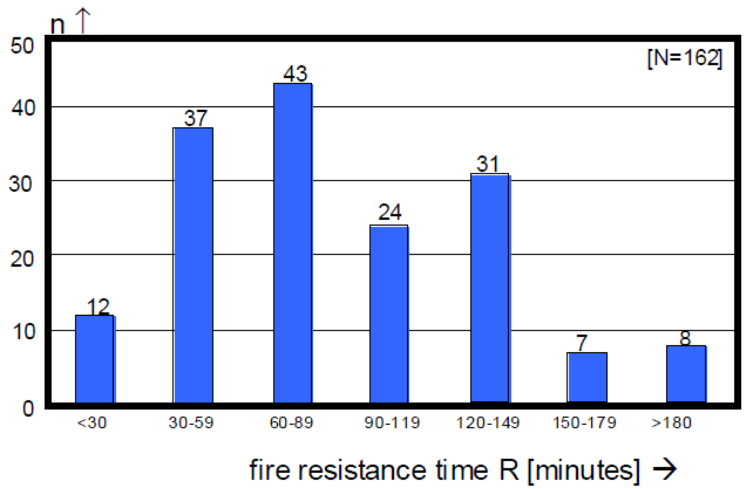
- Initiated in 2010 in order to gain a complete under-standing of the behaviour of prestressed concrete hollow-core slab floors under fire.
- European research project by
  BIBM, its members, and IPHA

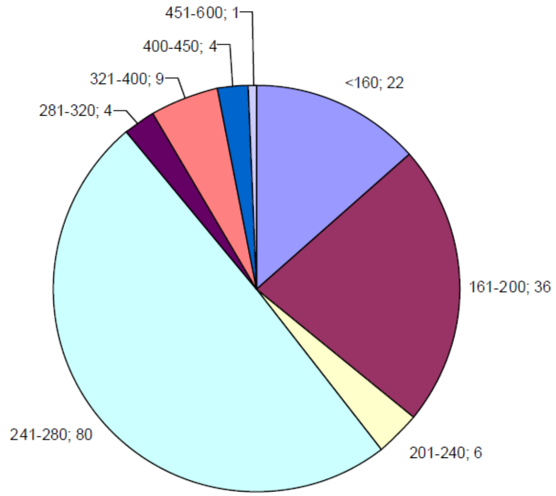
- **Contents of Holcofire**
  - **Desk research**
    - Literature research
    - Meta-analysis on database with 162 fire tests
    - Flexible supports
  - **Fire tests at Cerib (France)**
    - Shear and anchorage
    - Restraints on floor
  - **Simulations**
    - Finite Element Simulations (FEM)
    - Fire Dynamics Simulations (FDS5)
    - Numerical frame model
- End report was published in January 2014

Database on fire tests on hollow core slabs

- 162 fire tests made a meta-analysis possible



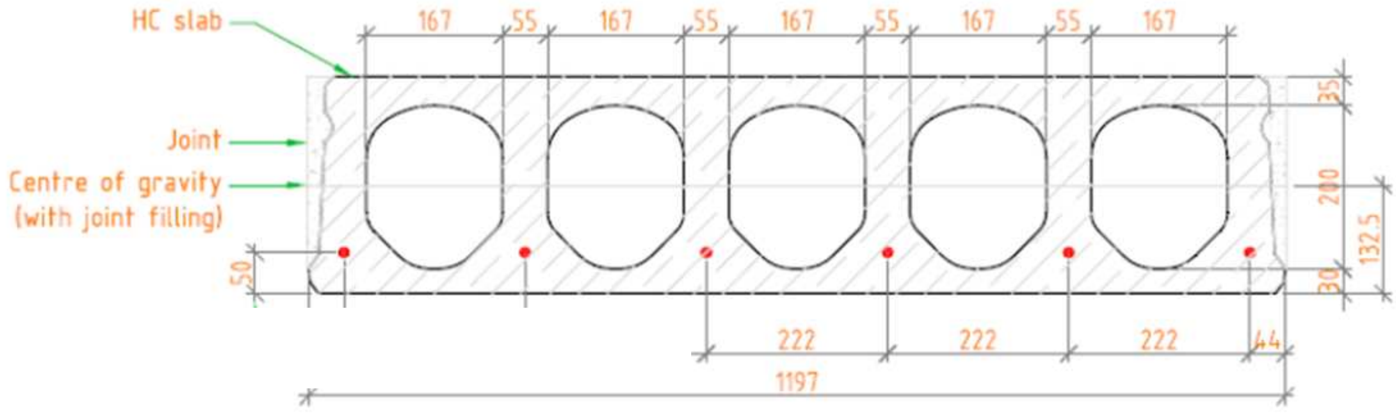




BRE	Building Research Establishment	United Kingdom
CBR	CBR Ergon laboratory	Belgium
CSI	CSI Gruppo IMQ	Italy
CTICM	Centre Technique Industriel de la Construction Metallique	France
CVUT	Technical University in Prague	Czech republic
DIFT	Danish Institute for Fire Technology	Denmark
EFNL	Efectis Nederland	Netherlands
FROSI	Fire Research Organisation Special Investigation	United Kingdom
IBS	Institut für Brandschutztechnik und Sicherheitsforschung	Austria
IG	Instituto Giordano - Laboratorio di Recherche di fiscica tecnica	Italy
ITB	Building Research Laboratory	Poland
EMPA	Eidg. Materialprüfungs- und Versuchsanstalt für Industrie, Bauwesen und Gewerbe (ETH Zurich)	Switserland
SPTRI	SP Technical Research Institute of Sweden	Sweden
RIFS	Ministry for Emergency Situations	Belarus
RUG	Rijksuniversiteit Gent	Belgium
TNO	Toegepast Natuurwetenschappelijk Onderzoek	Netherlands
TUB	Technische Universitat Braunschweig	Germany
UP	University of Perugia	Italy
VTT PAL	Valtion Teknillinen Tutkimuskeskus - Palotekniikan lab.	Finland
ZAG	ZAG fire laboratory	Slovenia

A meta-analysis is defined as a systematic method of evaluating data statistically, is based on results on the same problem of several independent studies, and produces stronger conclusions than can be provided by any individual study.

Holcofire fire tests G2/G3 (shear test)



HCS265

Concrete quality C45/55
A_c = 168467 mm^2
Total web width b_w = 326 mm

A_p = 6 x ∅12.5 = 558 mm^2
Axis distance e_p = 50 mm

Bending capacity M_{Rd} = 176 kNm/slab
Shear tension capacity V_{Rd} = 126 kN/slab
Flexural shear capacity V_{Rd} = 84 kN/slab

3. BENDING CAPACITY UNDER FIRE

Bending capacity - principles

- The bending capacity of a hollow core slab exposed to fire may be calculated by using simplified calculation methods or can be assessed by tabulated data.
  - Tabulated data normally gives minimum floor thicknesses and a minimum axis distance of the prestressing strands to the exposed surface.
    - Translation from massive floor to hollow core floor → effective thickness of hollow core hollowcore slabs: $t_e = h \sqrt{(A_c / b \cdot h)}$

One-way reinforced solid slabs		
Fire Resistance [min]	Slab thickness [mm]	bars
REI 60	80	20
REI 90	100	30
REI 120	120	40
REI 180	150	55

Prestressed hollow core slab		
Fire Resistance [min]	Slab thickness [mm]	Axis distance strands [mm]
REI 60	130	35
REI 90	160	45
REI 120	200	55
REI 180	250	70

EN1992-1-2:2004E clause 5.2(7) and 5.2(8)

G2/G3
265 – 50 mm
T_{crit} = 413ºC< 500ºC

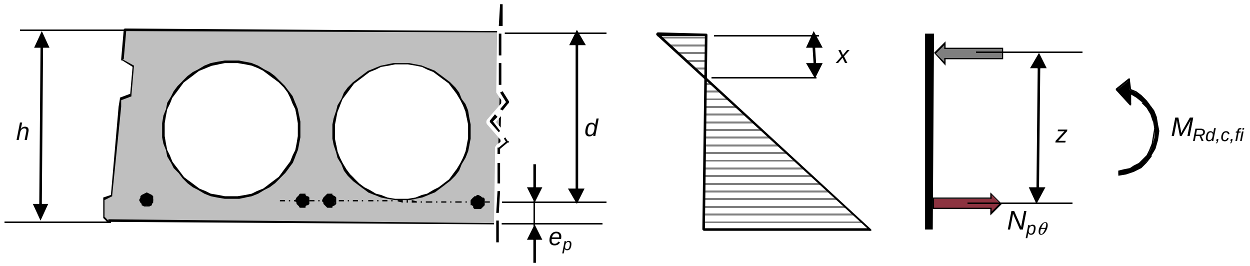
- The larger the axis distance, the lower the temperature in the strands, and thus the higher the fire resistance of the precast element.

Bending capacity – simplified calculation method

- The bending resistance of a hollow core slab is governed by the degradation of the strength of the prestressing strand in function of the temperature (the compression zone is hardly affected)

- The bending resistance under fire conditions $M_{Rd,c,fi}$ is:

$$M_{Rd,c,fi} = N_{p\theta}\, z$$



In which the parameters are

$N_{p\theta}$ = the maximum allowable force in the prestressing steel

$= \beta f_{pk}\, k_p(\theta)\, A_p$

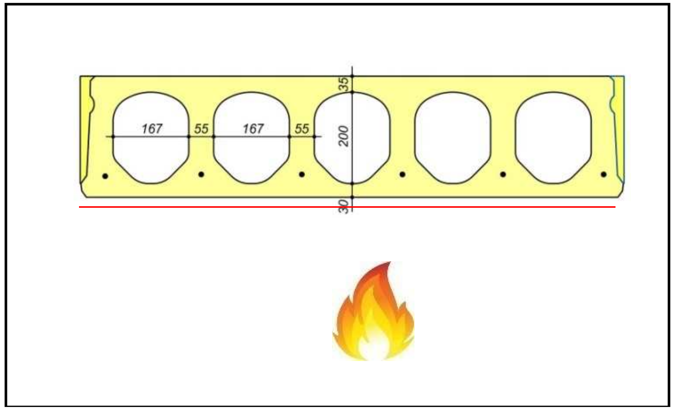
with β *= recommended value = 0,9 (class B)*

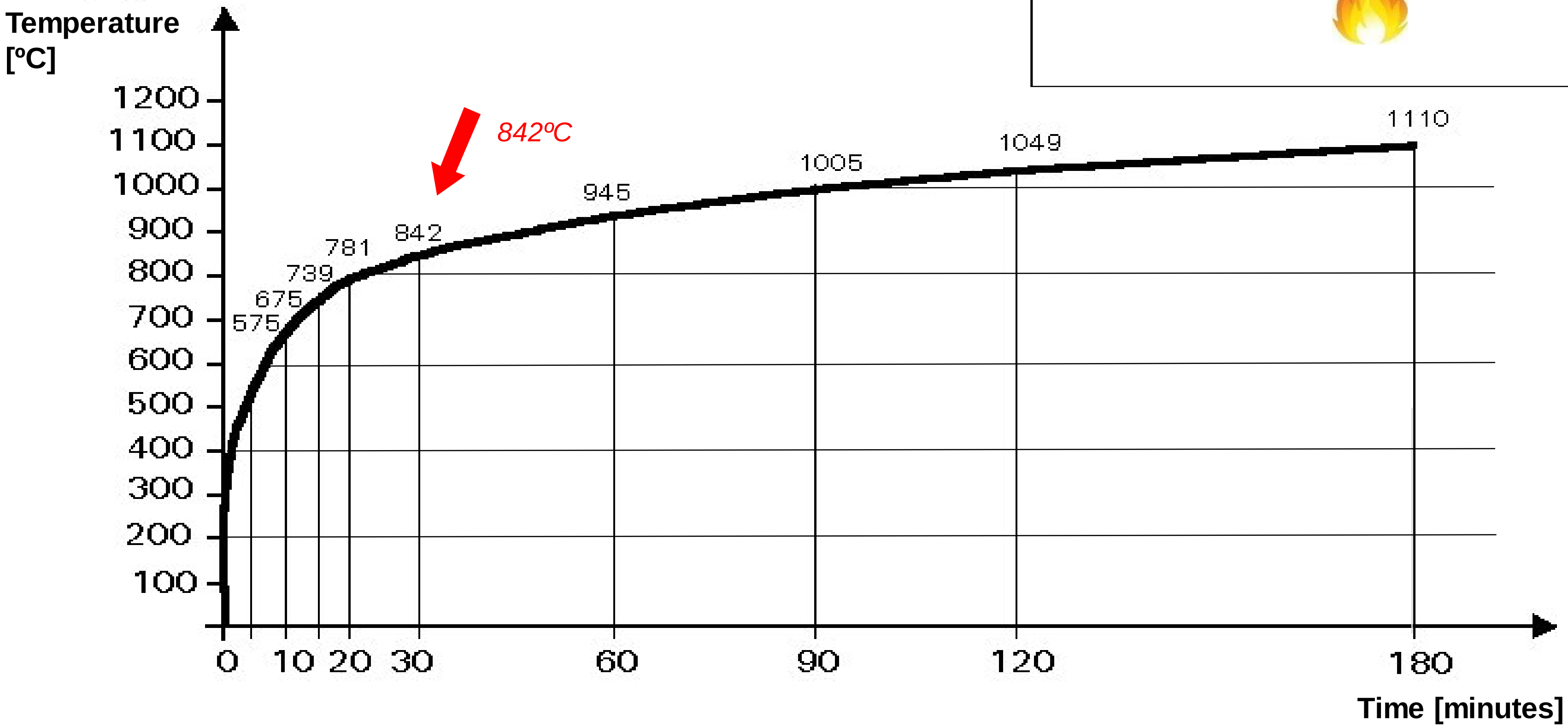
z = the internal lever arm

$\cong 0{,}9\,(h + h_{topping} - e_p)$

Standard ISO 834 fire

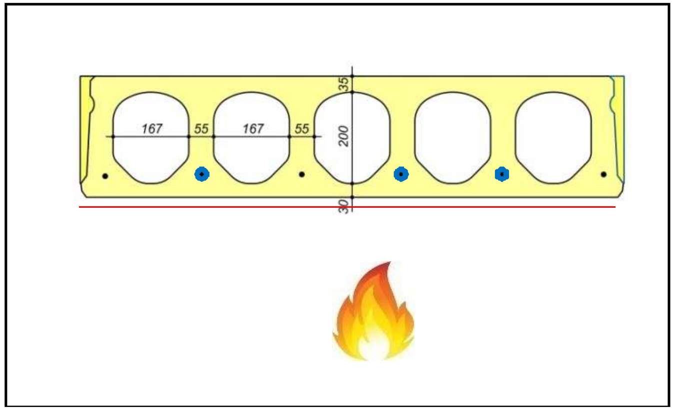
- The soffit of a hollow core slab / floor is exposed to the standard fire regime reaching 842 ºC in 30 minutes

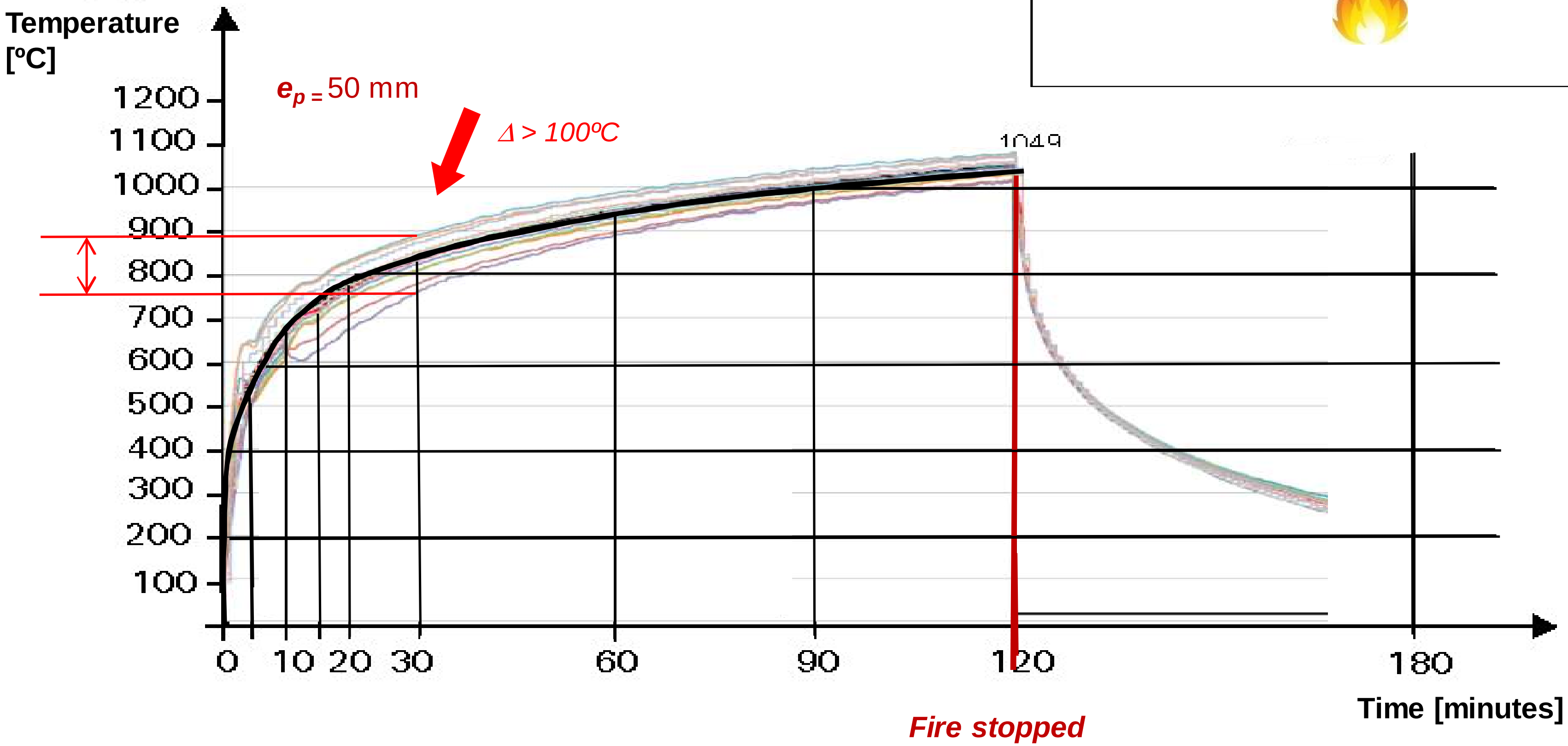




Standard ISO 834 fire in practice

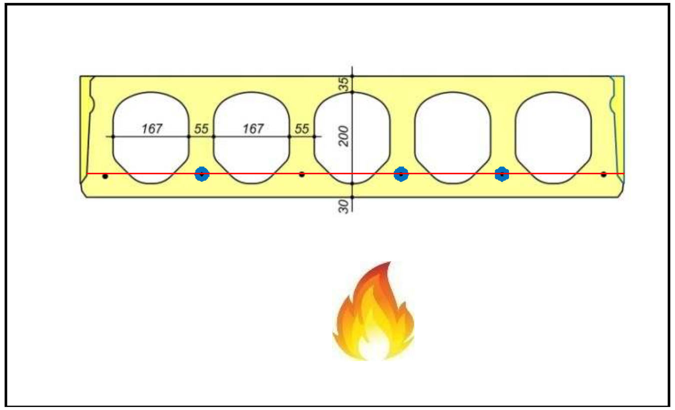
- In practice the scatter at 30 minutes is more than 100ºC: 880ºC-760ºC:

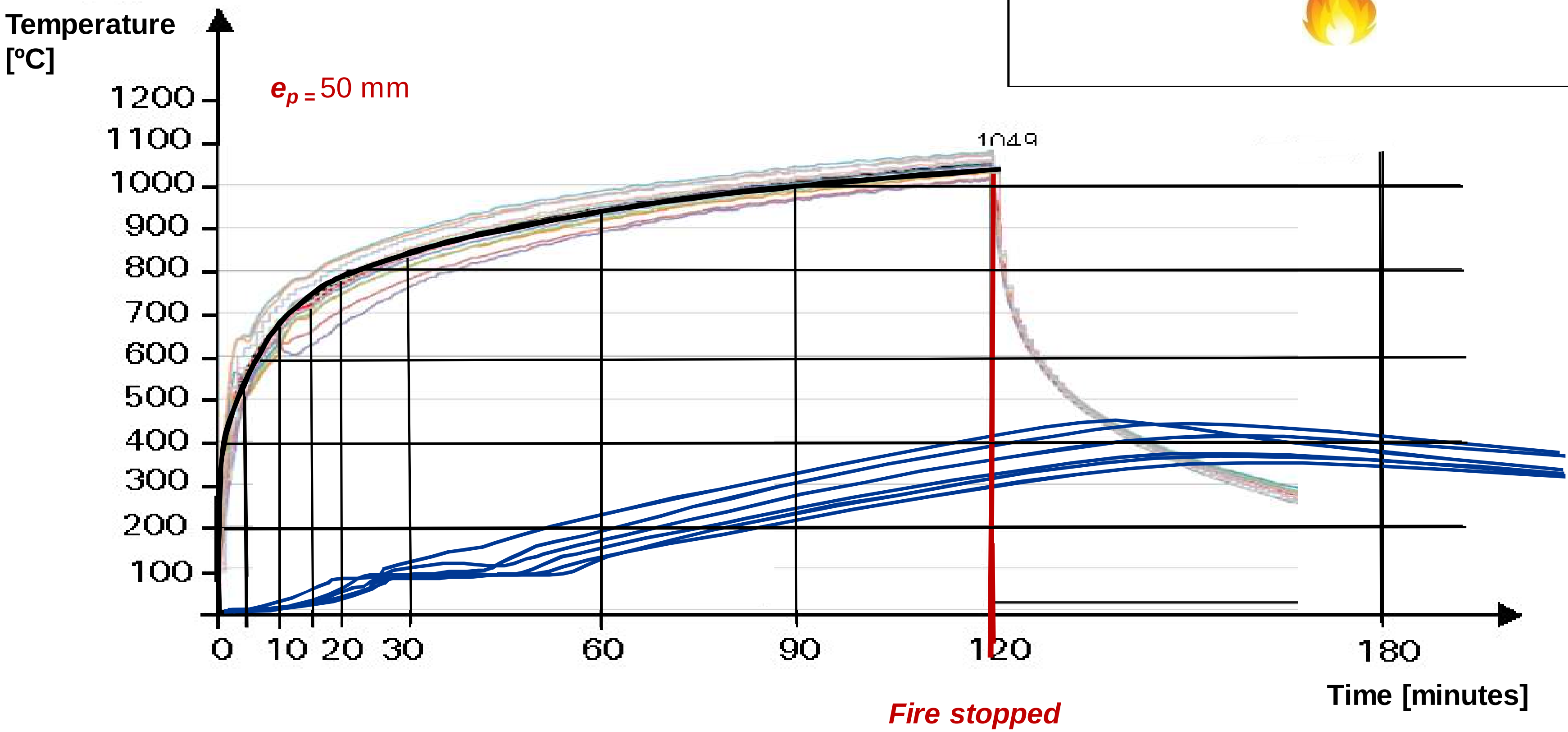




Fire test of G2/G3 – measured strand temperature

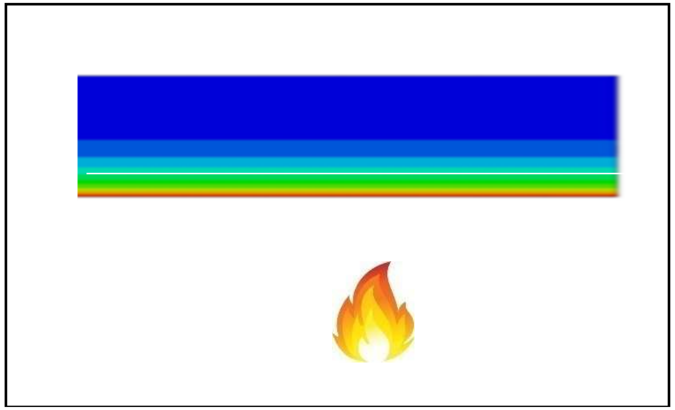
- During the shear tests with fire regime of 120 minutes the temperatures in the strands were registered

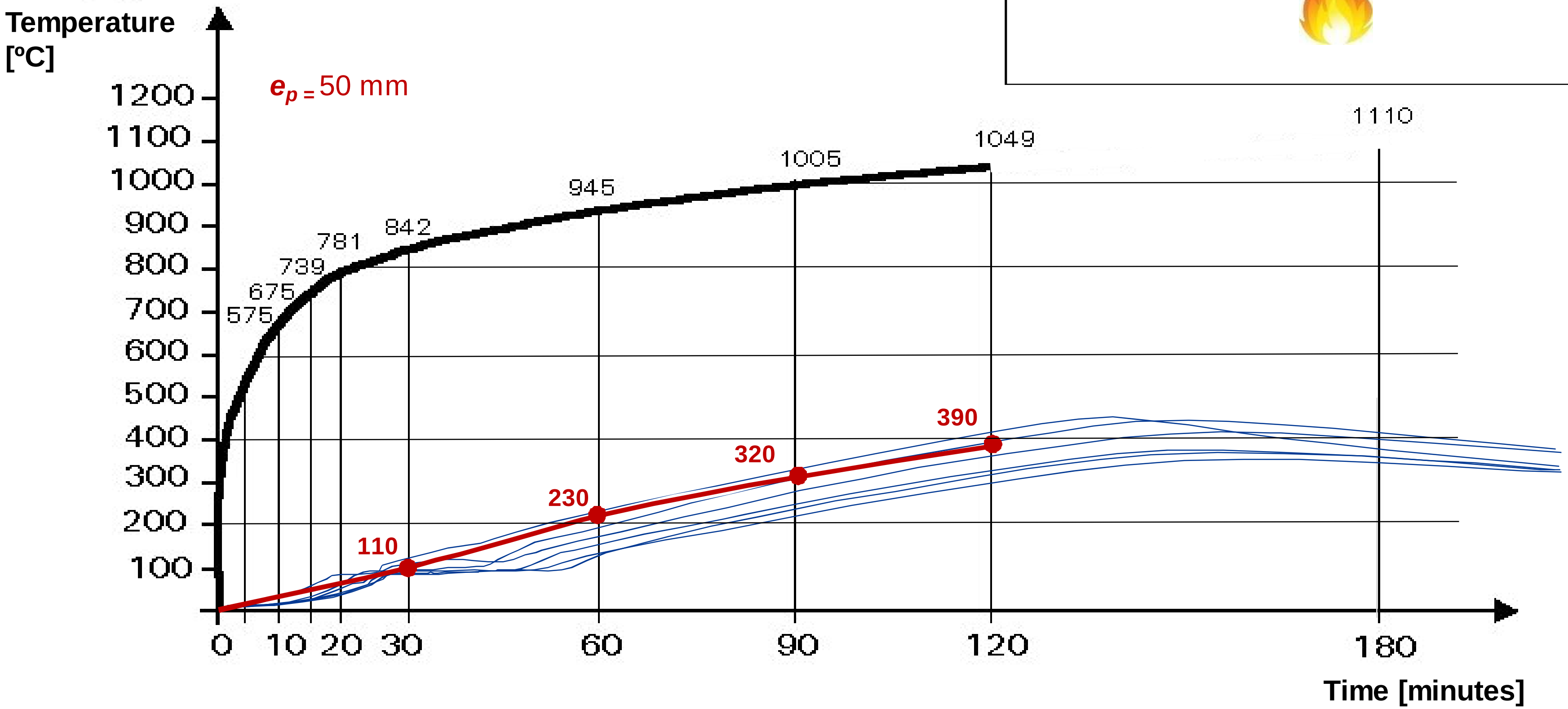




Fire test of G2/G3 – theoretical strand temperature

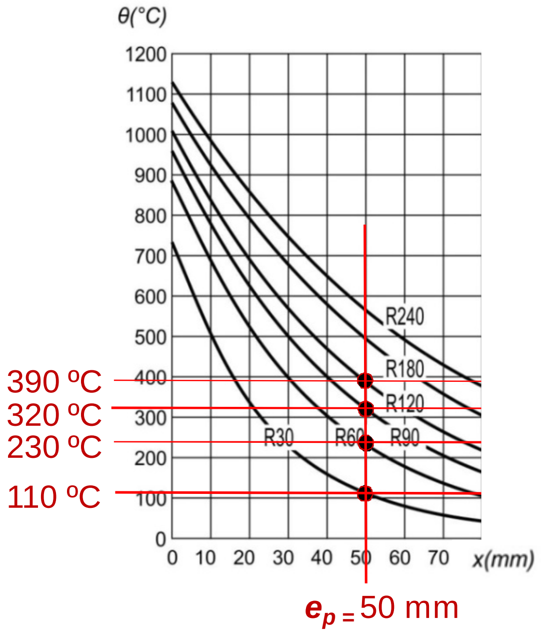
- Using analytical or numerical model we can calculate the theoretical strand temperature -> theory/practice

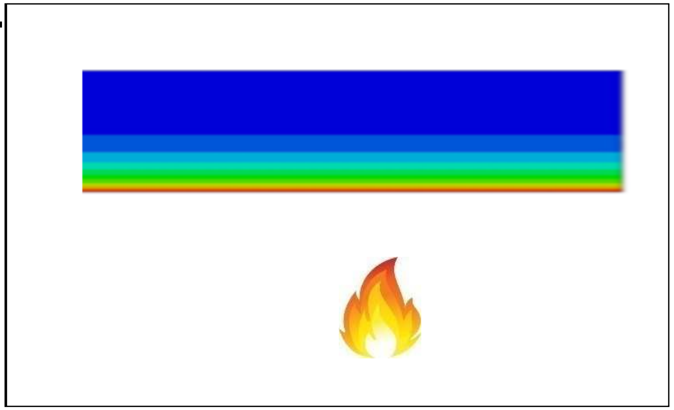




Fire test of G2/G3 – graphs in codes

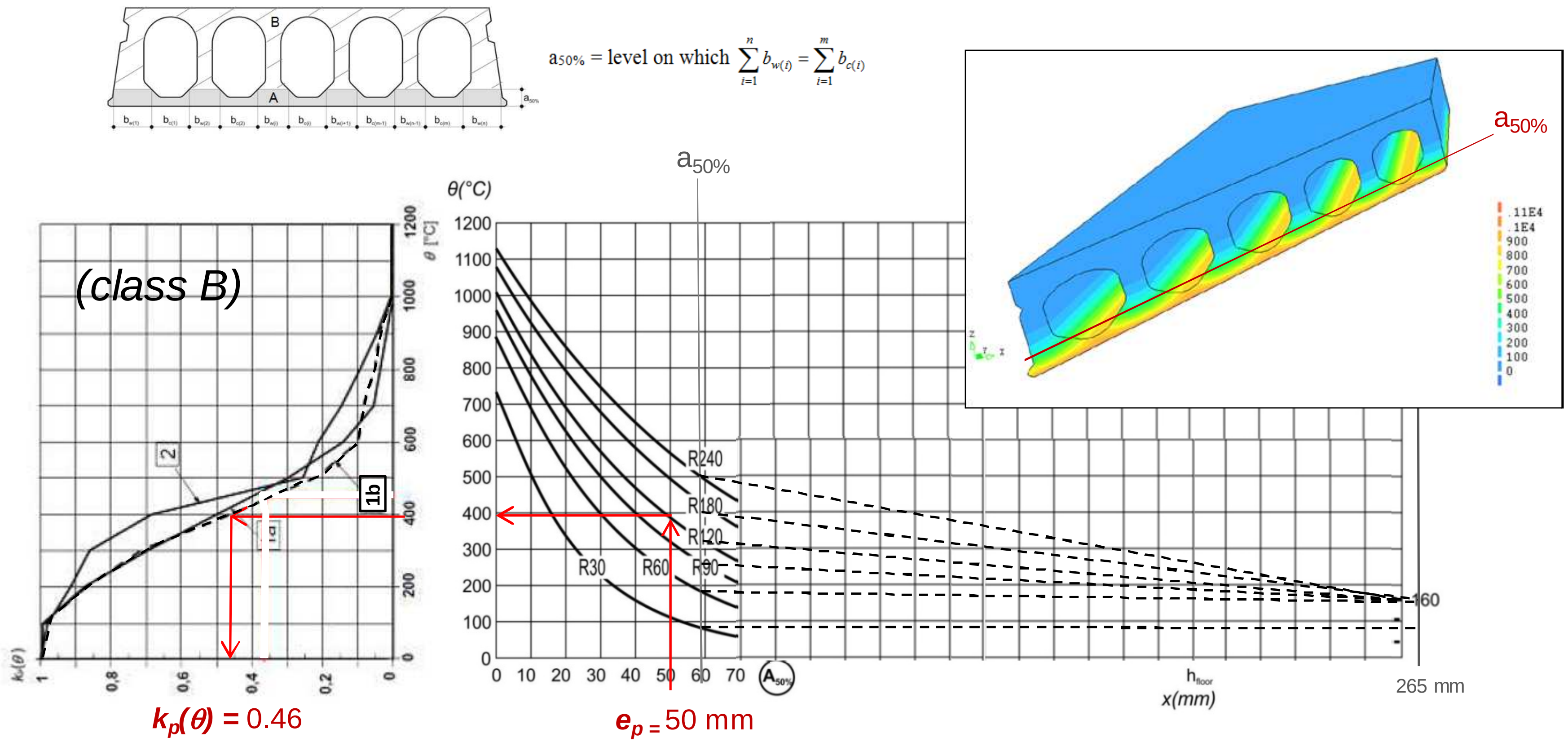
- Graphs have been developed to read out in order to get the theoretical strand temperature.
- With the use of for example EN1992-1-2 Figure A.2 one finds then that at an axis distance of 50 mm and 120 minutes the calculated strand temperature is 390 ºC.
-





G2/G3 – Strength of strands after 120 minutes

- With the use of for example EN1992-1-2 Figure 4.3 one can read out that the strength reduction of the strand is 54% and its strength has reduced to $\beta f_{pk}\, k_p(\theta)\, A_p$ = *0.9 x 1860 x 0.46* = 770 N/mm^2



Bending capacity – simplified calculation method

- The bending resistance of a hollow core slab is governed by the degradation of the strength of the prestressing strand in function of the temperature.

- The bending resistance under fire conditions $M_{Rd,c,fi}$ is:

  $M_{Rd,c,fi} = N_{p\theta}\, z$ = 430 x 0.194 = 84 kNm / slab → $M_{Rd,c,fi}$ = 47% M_{Rd} = 176 kNm/slab)

- In which the parameters are

  $N_{p\theta}$ = the allowable force in the prestressing steel → $\sigma_{p,fi}$ = 770 N/mm^2

  $= \beta f_{pk}\, k_p(\theta)\, A_p$ = 0.9 x 1860 x 0.46 x 558 = 430 kN /slab

  with β = recommended value = 0,9 (class B)

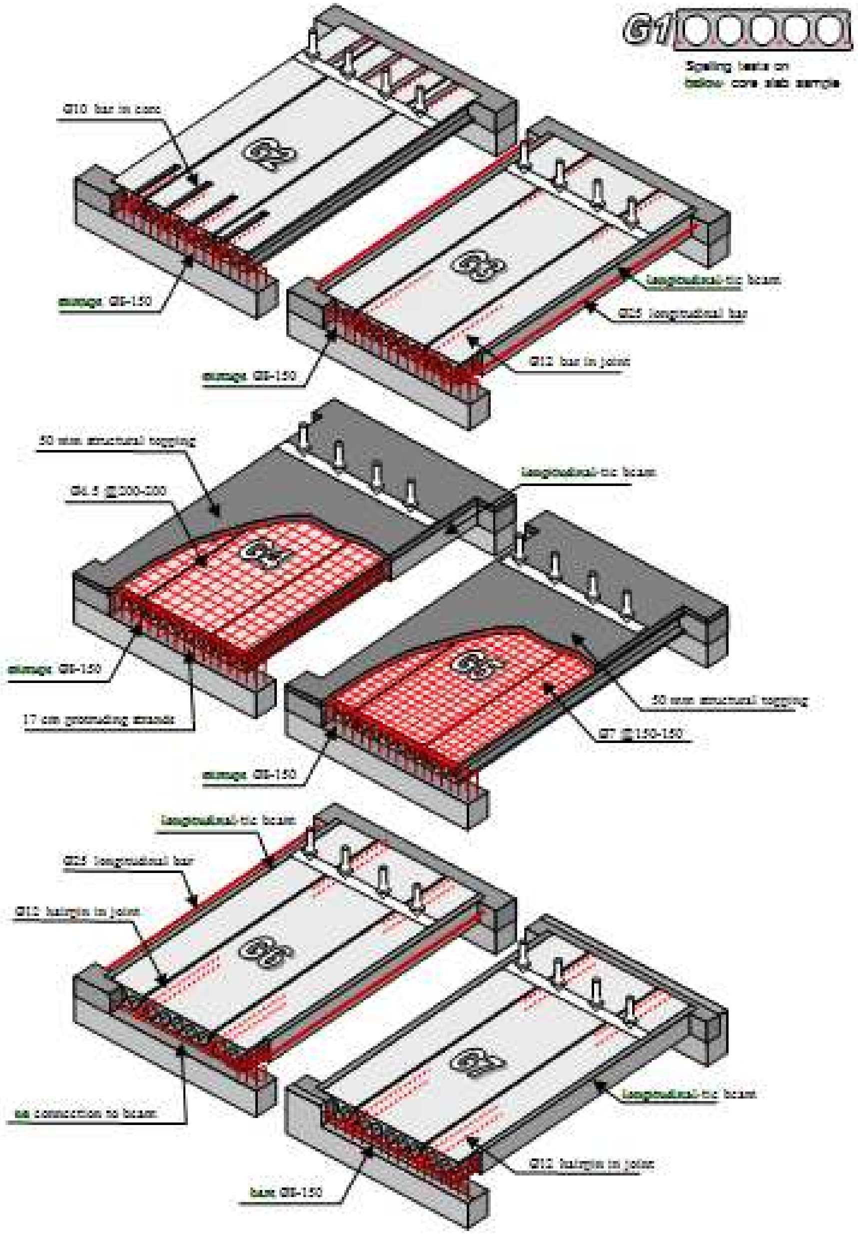
  z = the internal lever arm

  $\cong 0{,}9\,(h + h_{topping} - e_p)$ = 0.9x(265 + 0 - 50) = 194 mm

4. SHEAR AND ANCHORAGE CAPACITY UNDER FIRE

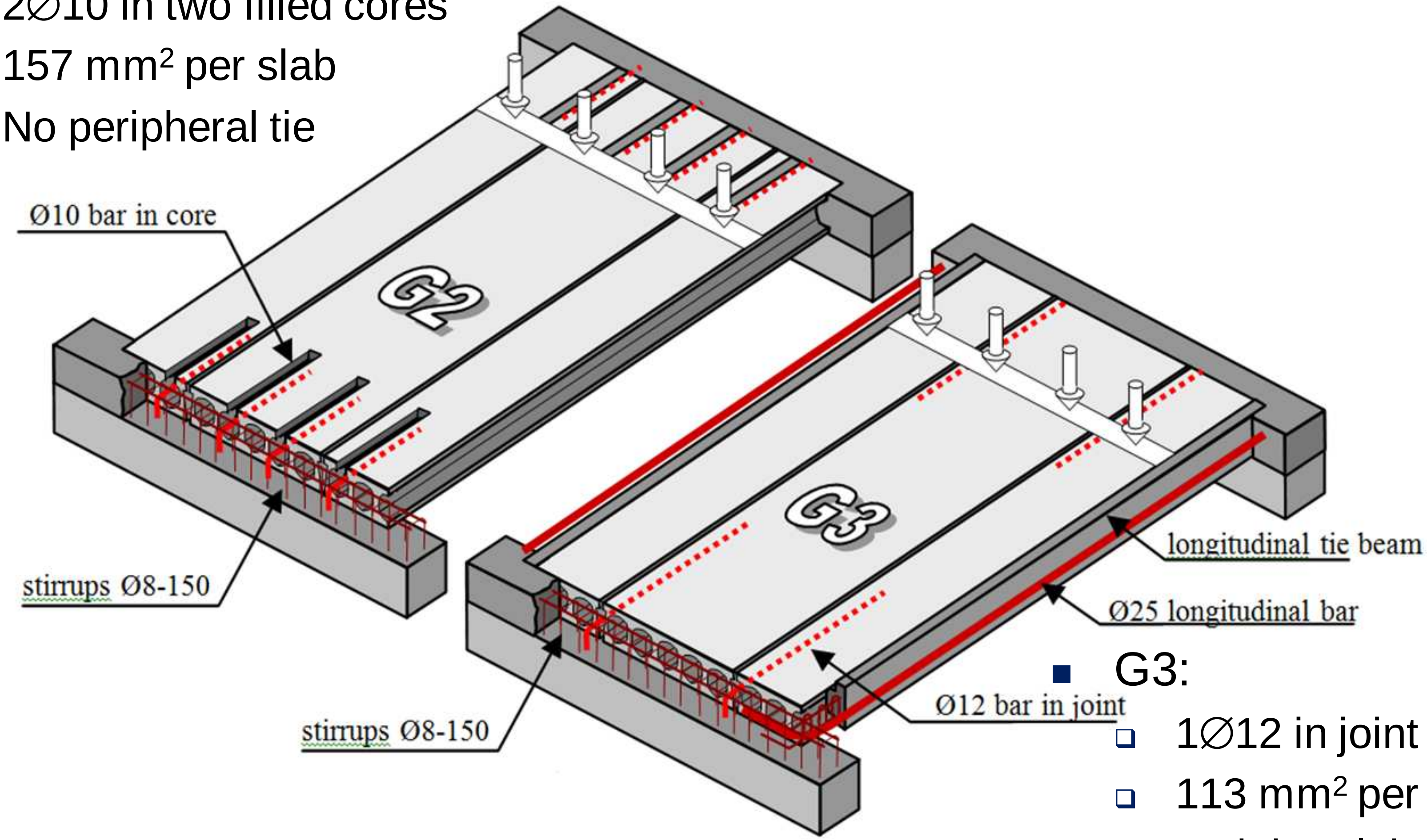
G-series to verify EN1168 Annex G

- Tests were designed as EN1168 Annex J tests, but with fire to test shear and anchorage
  - Executed at CERIB – France
  - Spalling tests G1
  - shear tests G2/G3, G4/G5, G6/G7 with country specific parameters



Shear and anchorage under fire – G2/G3

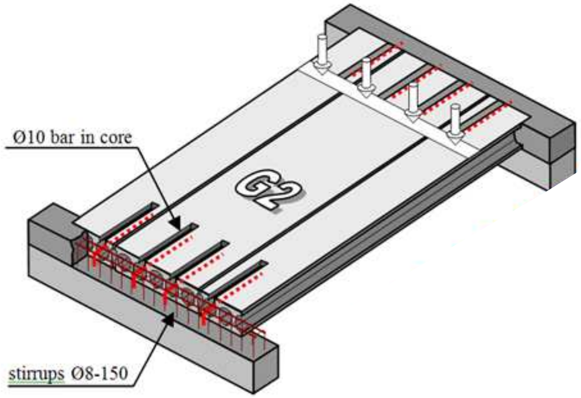
- G2:
  - 2∅10 in two filled cores
  - 157 mm^2 per slab
  - No peripheral tie

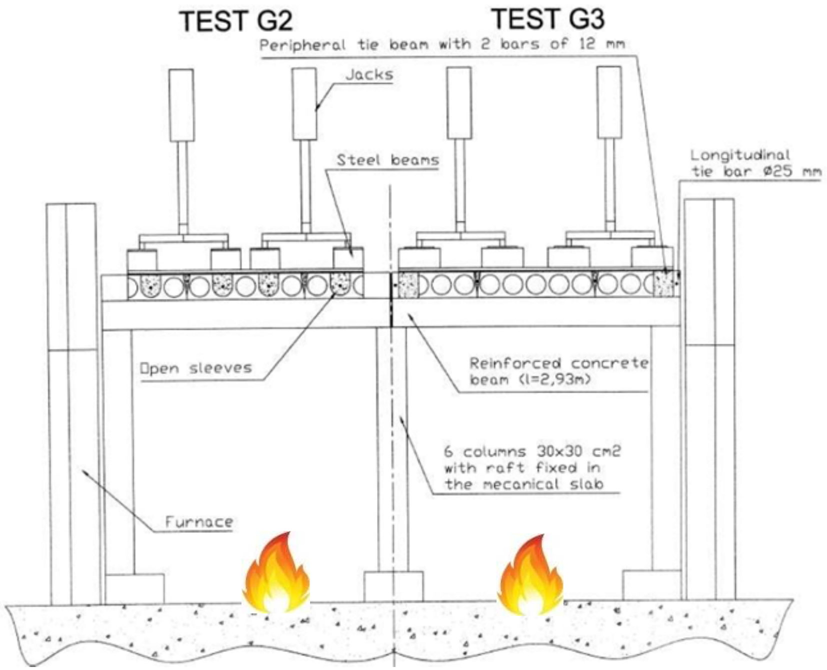


- G3:
  - 1∅12 in joint
  - 113 mm^2 per slab
  - peripheral tie
  - External bar ∅25

Holcofire fire shear tests G2

- Floors G2 (and G3) were loaded with 120 minutes of ISO fire
- During the fire a live load was applied by jacks at a distance of 2.5 h (Annex J) from the support
- Load was increased after the fire test up to failure





Core view in G2 at 16 minutes of fire

Core view in G2 at 18 minutes of fire

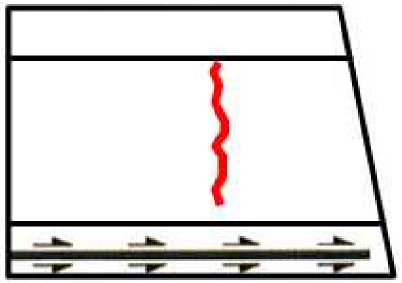
Core view in G2 at 23 minutes of fire

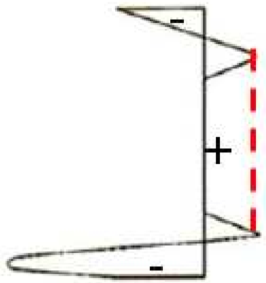
Core view in G2 at at 47 minutes of fire

G2 floor after 120 min fire and after shear loading

Vertical web cracking

- The shear capacity of prestressed hollow core slabs during fire is affected by the increase of the tensile stresses in the webs due to the temperature gradient, degradation of the strength of the concrete and the increase of the transfer length of the prestressing tendons due to possible strand slippage
- Calculations show that the tensile stresses in the central zone are exceeding the tensile capacity of the concrete after about 20 to 40 minutes in a standard ISO fire, and that vertical cracks are appearing in the webs at regular intervals of about 150 to 200 mm spacing



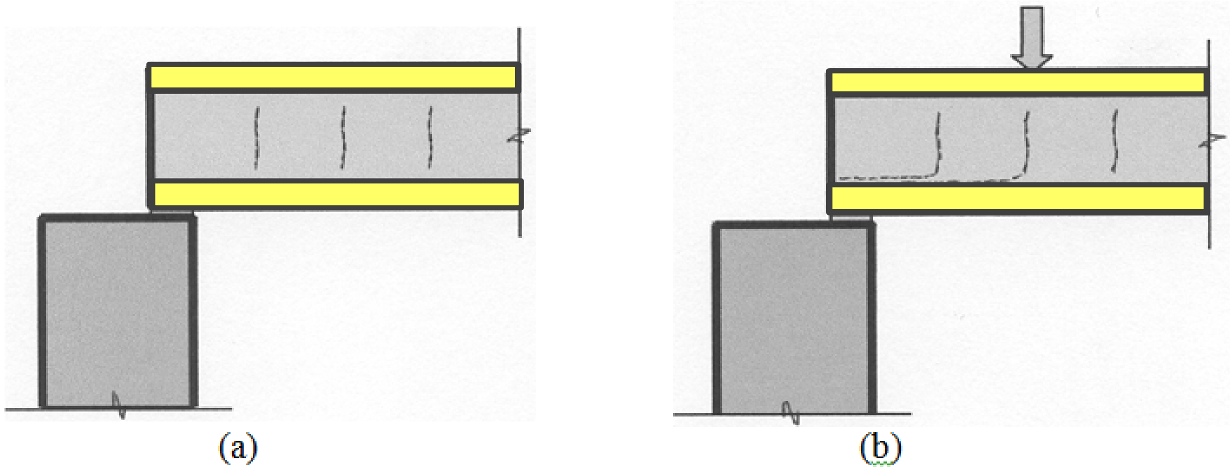


Shear failure mode

- Failure mode of a hollow core slab in shear during fire:

  (a) shows the appearance of vertical cracks due to differential thermal deformation over the cross-section;

  (b) shows the propagation of the vertical cracks into horizontal cracks due to additional shear loading and thermal effects.



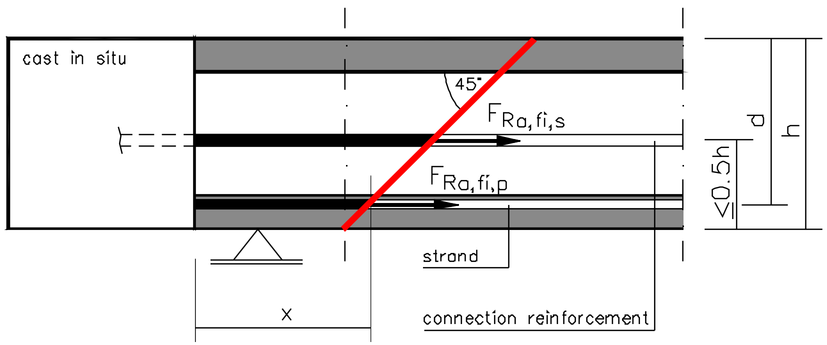
- To assure adequate shear capacity, possible cracks in the webs of the hollow core units should be kept closed to enable shear transfer by aggregate interlock mechanism.
- This is normally realized through the connections within the supporting structure

Shear capacity – EN1168 Annex G formula

- The shear resistance of a hollow core slab is governed by the degradation of the strength of the concrete and anchored connection reinforcement
- The empirical shear equation under fire conditions is:

  $V_{Rd,c,fi} = [C_{\theta.1} + \alpha_k C_{\theta.2}]\, b_w\, d$

  - $C_{\theta.1}$ coefficient for the concrete stress under fire
  - $C_{\theta.2}$ coefficient for the anchored longitudinal reinforcement under fire
  - α_k $1+\sqrt{\frac{200}{d}} \leq 2.0$
  - b_w total web thickness
  - d effective depth at ambient temperature ($h_{slab} – e_p + h_{topping}$)

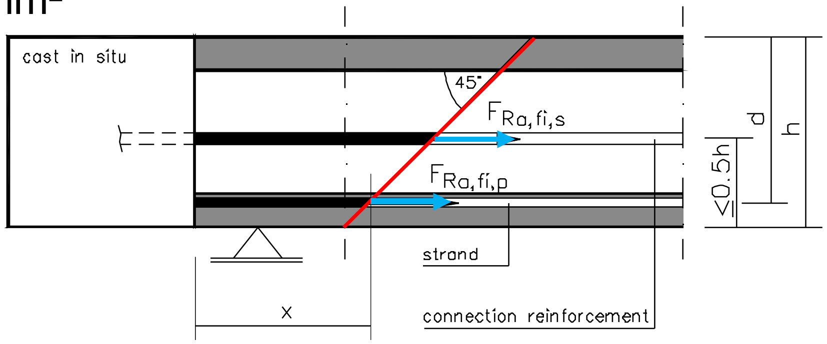


[EN1168:2005+A3:2011 Annex G]

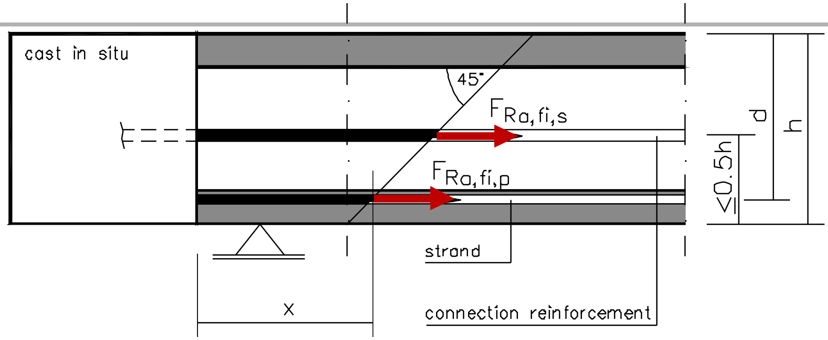
Coefficient concrete stress under fire in test G2

- $$C_{\theta.1} = 0.15 \cdot \min(k_p(\theta_p) \cdot \sigma_{cp,20^oC}\ ;\ \frac{F_{R,a,fi,p}}{A_c})$$
  $$= 0.15 \cdot \min(0.46 \cdot 3.3\ ;\ \frac{34820}{168467})$$
  $$= 0.15 \cdot \min(1.52\ N/mm^2;\ 0.21\ N/mm^2) = 0.032$$

  - θ_p = 390ºC
  - k_p = 0.46 for 390ºC
  - $\sigma_{cp,20^oC} = A_p\ \sigma_{p,20^oC} / A_c = 558 \cdot 1000 / 168467 = 3.3\ N/mm^2$
  - $F_{R,a,fi,p}$ = force capacity prestressing steel (390ºC)
    $= A_p \min(f_{bpd,fi}\ x / \alpha_2\varnothing;\ f_p\ k_p(\theta_p)) = 558 \cdot \min(62\ ;\ 770) = 34820$ N
  - $A_c = 168467\ mm^2$



Coefficient anchored longitudinal reinforcement under fire in test G2



- $C_{\theta.2} = \sqrt[3]{0.58 \dfrac{F_{R,a,fi}}{f_{yk} \cdot b_w \cdot d} f_{c,fi,m}}$

  $= \sqrt[3]{0.58 \dfrac{113320}{500 \times 326 \times 215} 46.4} = 0.44$ - 6∅12.5 strands plus 2∅10 bars

  $= \sqrt[3]{0.58 \dfrac{34820}{500 \times 326 \times 215} 46.4} = 0.30$ - only 6∅12.5 strands

- $F_{R,a,fi} = F_{R,a,fi,p} + F_{R,a,fi,s} = 34820 + 0/78500 =$ 34820 N and 113320 N (6∅12.5) (6∅12.5+2∅10)
  - $F_{R,a,fi,p}$ = force capacity prestressing steel (390ºC)
    $= A_p \min(f_{bpd,fi}\, x / \alpha_2 \varnothing ; f_p\, k_p(\theta_p)) = 558 \cdot \min(62 ; 770) = 34820$ N
  - $F_{R,a,fi,s}$ = force capacity connection reinforcement (275ºC)
    $= A_s\, f_s\, k_s(\theta_s) = 157 \cdot 500 \cdot 1.0 = 78500$ N
- $f_{c,fi,m}$ = strength of concrete for temperature at mid height (275ºC)
  $= 0.875 \cdot 53 = 46.4$ N/mm^2

Shear and anchorage capacity of G2

- The empirical shear equation under fire conditions is:

- $V_{Rd,c,fi} = [C_{\theta.1} + \alpha_k C_{\theta.2}]\, b_w\, d$

  $= [0.032 + 1.96 \cdot 0.44] \cdot 326 \cdot 215 = 62.8$ kN/slab plus 2∅10 bars

  = [0.032 + 1.96 · 0.30] · 326 · 215 = 43.3 kN/slab plus only strands

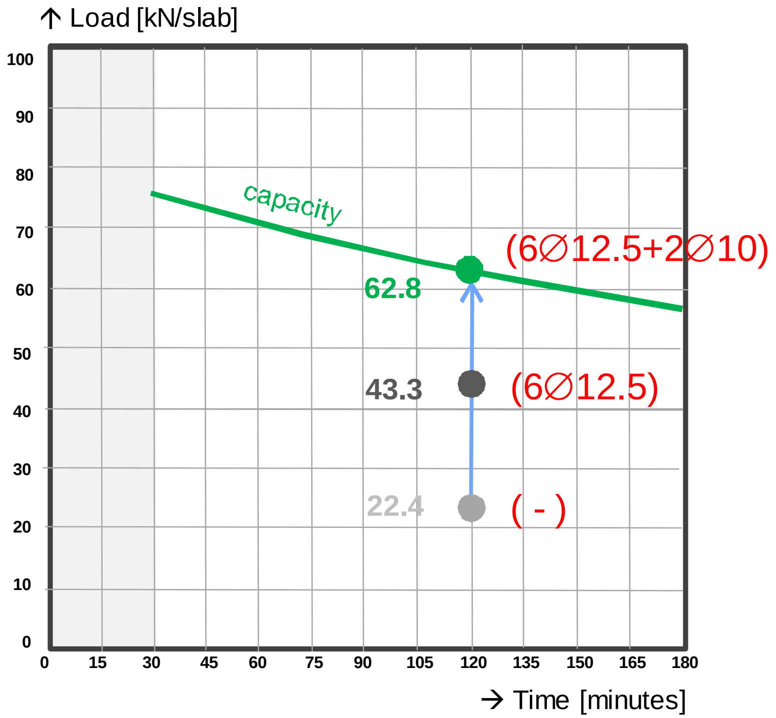
  = [0.032 + 1.96 · 0.00] · 326 · 215 = 22.4 kN/slab only concrete stress)

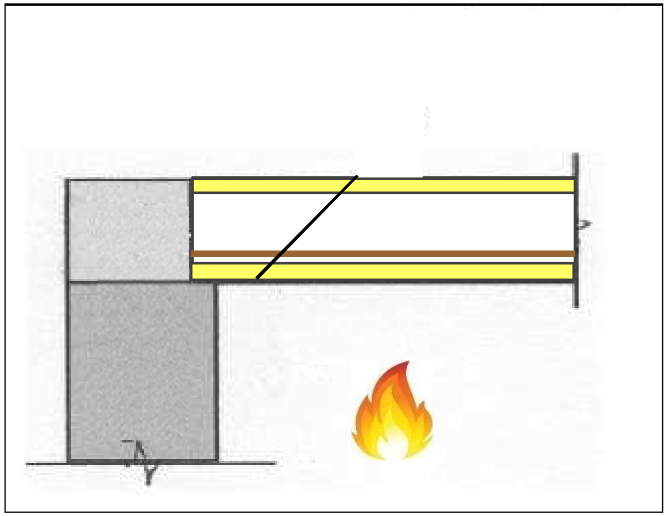
  - $C_{\theta.1}$ = 0.44 (coefficient for the concrete stress under fire)
  - α_k = $1 + \sqrt{(200/215)} = 1.96 \leq 2.0$
  - $C_{\theta.2}$ = 0.30 (6∅12.5 anchored reinforcement under fire)
    0.44 (6∅12.5 + 2∅10 anchored reinforcement under fire)
  - b_w = 326 mm (total web thickness)
  - d = 265 – 50 = 215 mm (effective depth at ambient temperature)

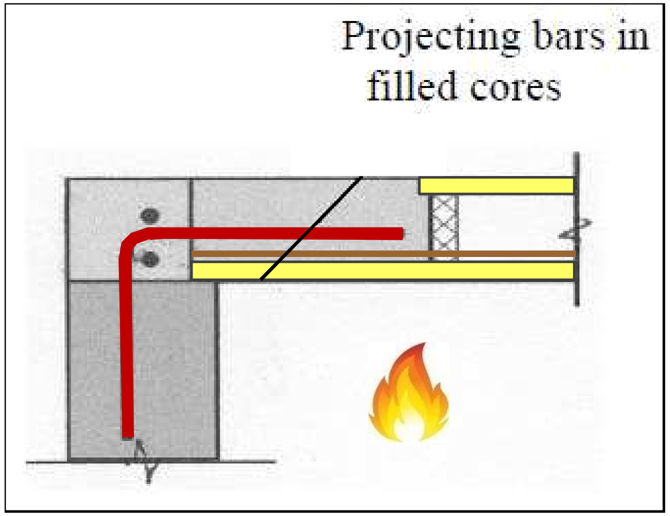
Shear and anchorage capacity of G2 analysed

- The empirical shear equation under fire

$$V_{Rd,c,fi} = \left[C_{\theta.1} + \alpha_k \cdot C_{\theta.2}\right] \cdot b_w \cdot d$$







Fire test capacities in shear tests G2 and G3

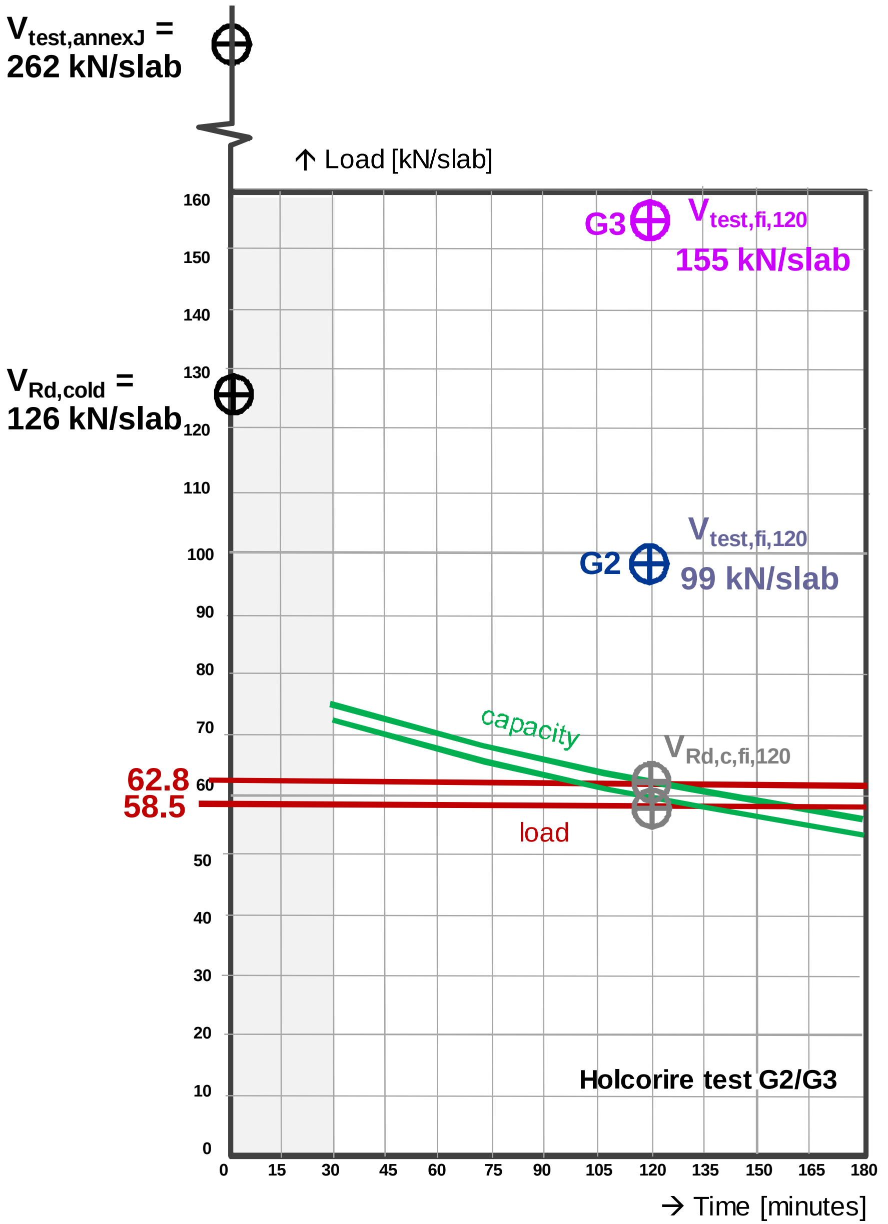
G2 158%

G3 266%

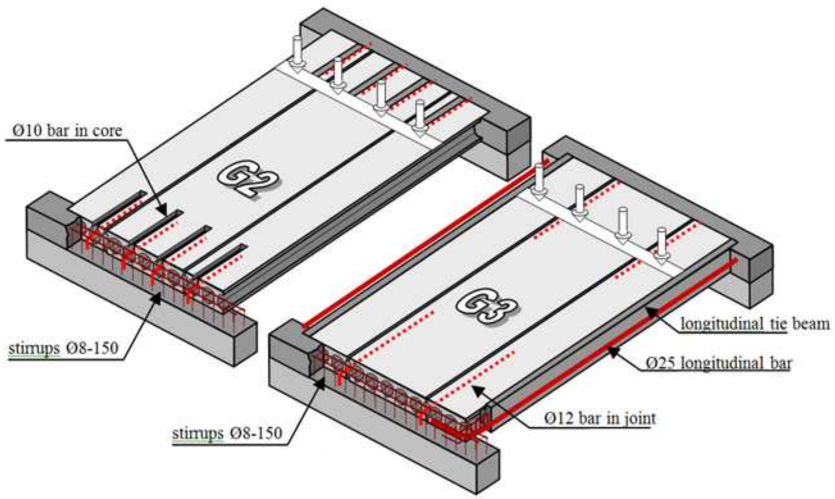
Real shear tension capacity at 20ºC: V_{test} = *262 kN/slab*

Design shear tension capacity at 20ºC: V_{Rd} = *126 kN/slab*

Fire test loads in shear tests G2 and G3

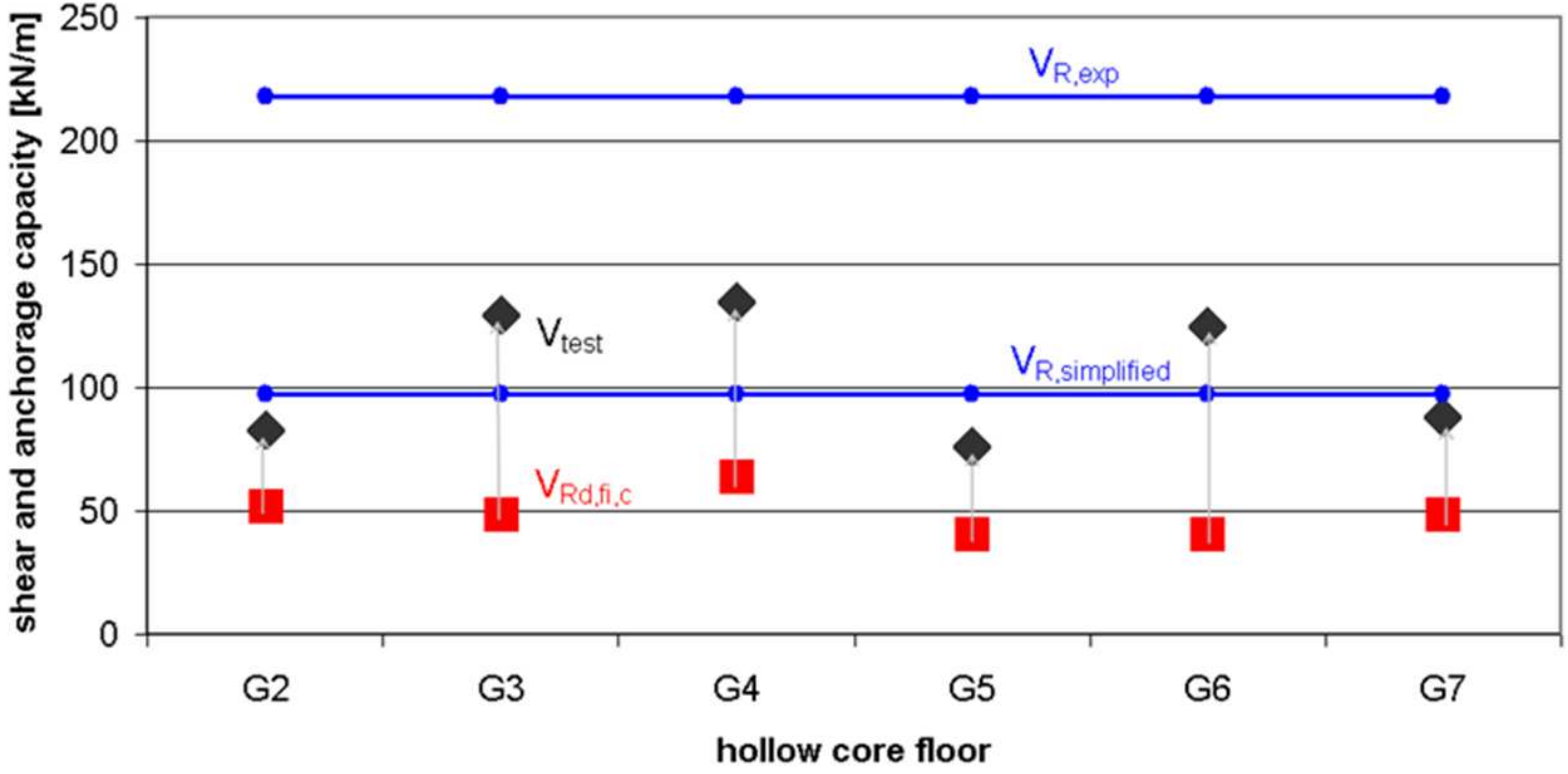


- G2: 2∅10 in two filled cores
  - 157 mm² per slab
  - no peripheral tie



- G3: 1∅12 in joint
  - 113 mm² per slab
  - peripheral tie
  - externnal bar ∅25

Holcofire G tests



2∅10 in two filled cores
No peripheral tie

1∅12 in joint
peripheral tie
External bar ∅25

50 mm topping
Protruding strands
peripheral tie

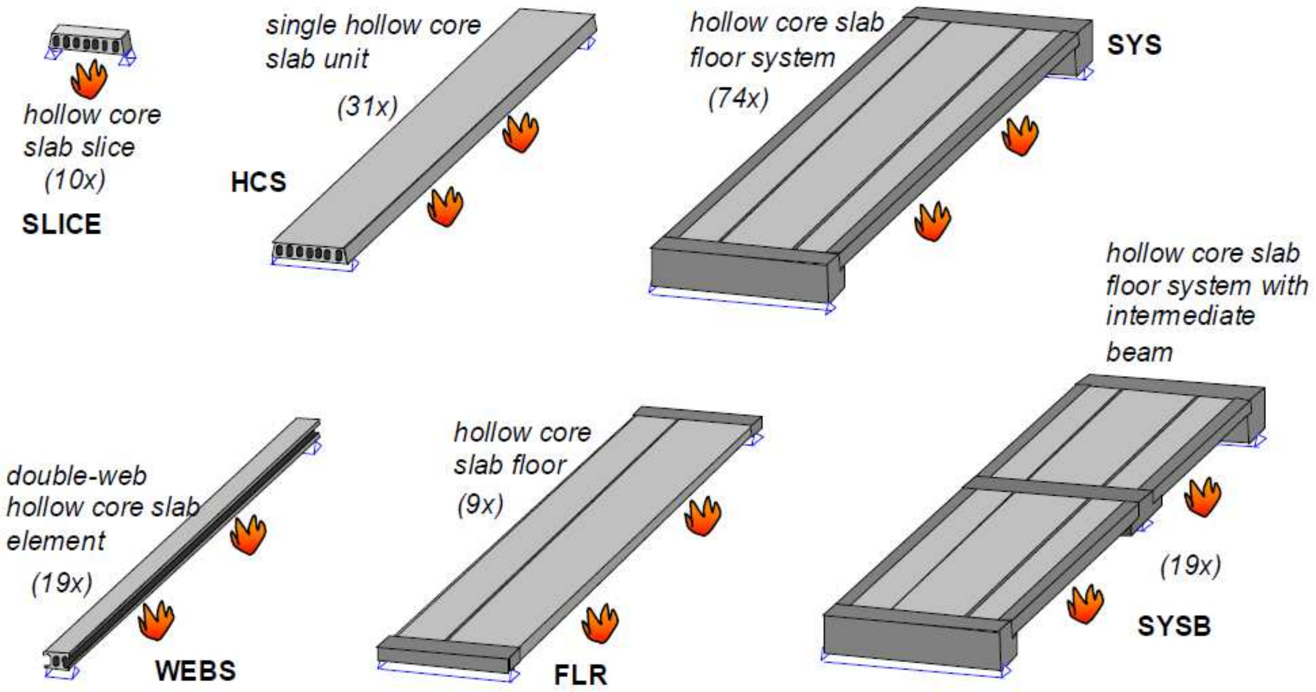
50 mm topping

1∅12 in joint
peripheral tie
External bar ∅25

1∅12 in joint
peripheral tie

Systems effect increases real capacity

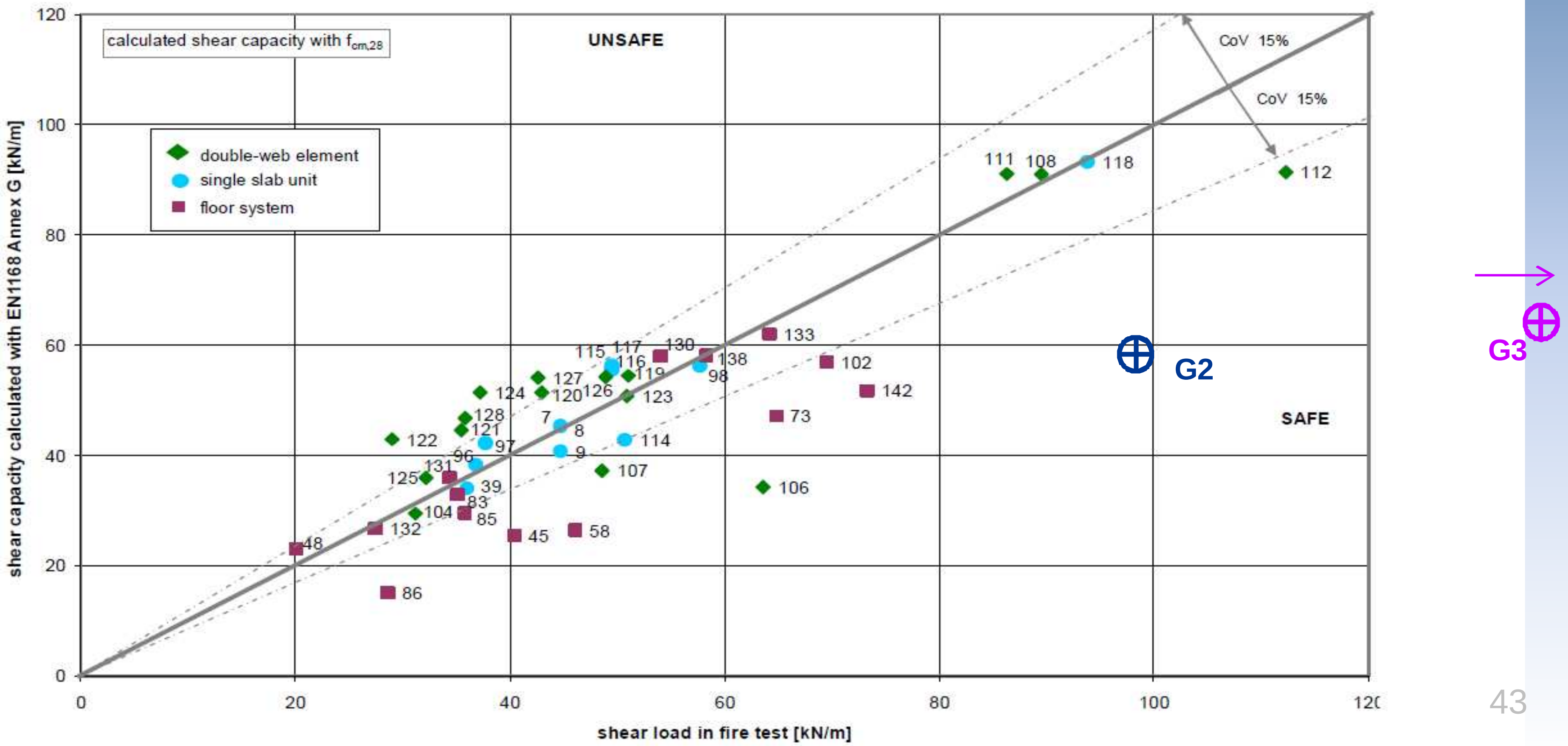
- The "*system effect*" is an increase in shear capacity mainly caused by the introduction of a longitudinal blocking effect that closes the vertical cracks and acts positively on the shear and anchorage capacity.
- This system effect is not taken into account in the empirical formula and thus is additional safety.



Meta-analyses on EN1168 Annex G

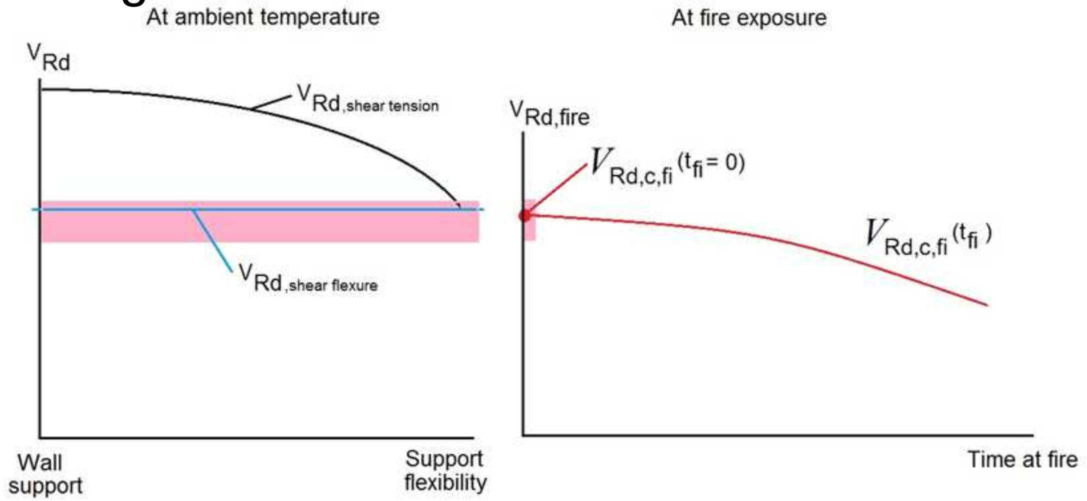
- The empirical formula has been confirmed in the Holcofire project.
  - In general from six G test in Holcofire
  - 42 fire independent fire tests that exhibited shear and anchorage failure
  - 102 independent fire tests that reached the required resistance time

$$V_{Rd,c,fi} = [C_{\theta.1} + \alpha_k C_{\theta.2}]\, b_w\, d$$



Hollow core units on flexible supports in fire

- It was concluded in Holcofire project that also for hollow core slabs flexible supports, EN1168 Annex G can be used for determining the shear and anchorage resistance under fire conditions.
  - On the one hand, the underflange of the hollow core slabs expands and is under compression such that the additional bending stresses are compensated.
  - On the other hand, vertical thermal cracks occur in the webs of the hollow core units such that a shear tension failure cannot occur anymore, because the section is cracked.
- As a result, the shear resistance under fire "falls back" to the level of shear resistance according to Annex G which decreases in time.



5. SPALLING AND RESTRAINTS ON FLOORS

Holcofire G2 after 120 min of fire – no spalling

Risk of spalling in hollowcore floors

- Spalling is not a specific problem for hollow core floors, but for concrete structures in general.
- According to Eurocodes explosive spalling is unlikely to occur when the moisture content is less than 3% by weight (recommended value).
- There are many parameters intervening in the risk of spalling:
  - Hollow core floors are generally less subjected to spalling than many other structural components, especially when cast in-situ.
  - Also the geometry of the cross-section is not unfavourable, and might be worse for other product.
  - Generally speaking, explosive spalling is not explicitly taken into account in the design of concrete structures.

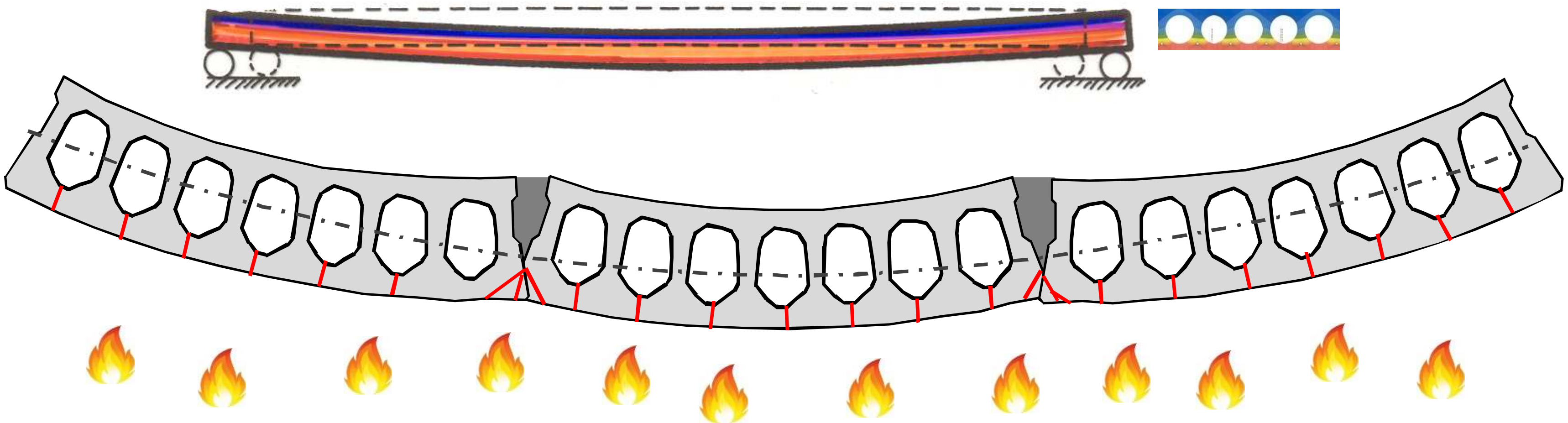
Due to concrete exposure to fire, free water in the concrete changes phase to steam. If the steam is not released through concrete due to its dense packing then it causes pieces breaking off: explosive spalling.

Moisture in buildings

- Also, the equilibrium moisture content in buildings is expected to be low in such a way that the risk of spalling is limited.
- Inside buildings, the equilibrium moisture content is normally in the range of 2-3% by weight when the concrete structure has reached a state of moisture equilibrium with the inside environment with a yearly average humidity of 40-50 % - residential, office
  - This implies that when the concrete structure has just been constructed, the moisture content in the concrete will be higher and it needs time to "dry out."
- For a concrete structure exposed to outside conditions (relative humidity 83%) higher equilibrium moisture content in the concrete structure can be expected – carpark, stadium
  - Accordingly, just constructed concrete buildings and open concrete buildings are more sensitive to spalling, for precast as well as cast in-situ structures.

Edge spalling due to free expansion

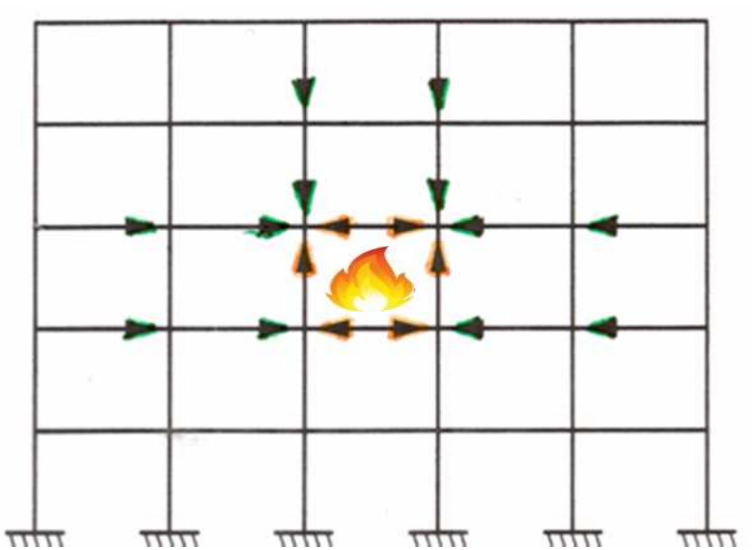
- Due to free expansion of the exposed soffit horizontal forces in the under flange of the hollow core slab will occur.
- In floors with slabs (without topping or normal topping) the floor can will bend towards the fire.

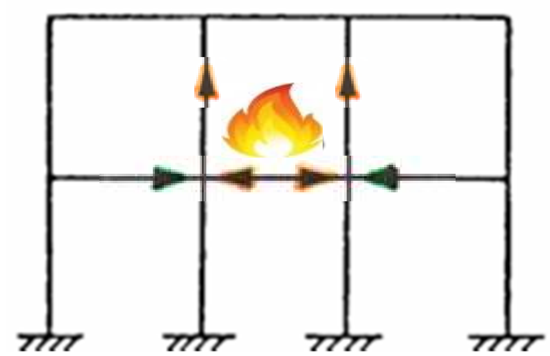


- These forces can lead to local damage at the edges of the units. In general these local damages result in release of the horizontal blocking forces.
- Occurrence of “I-beams”

Blocking in floors – external restraint

- Due to fire, in buildings blocking can occur in various directions that hinders expansion of the hollowcore floor



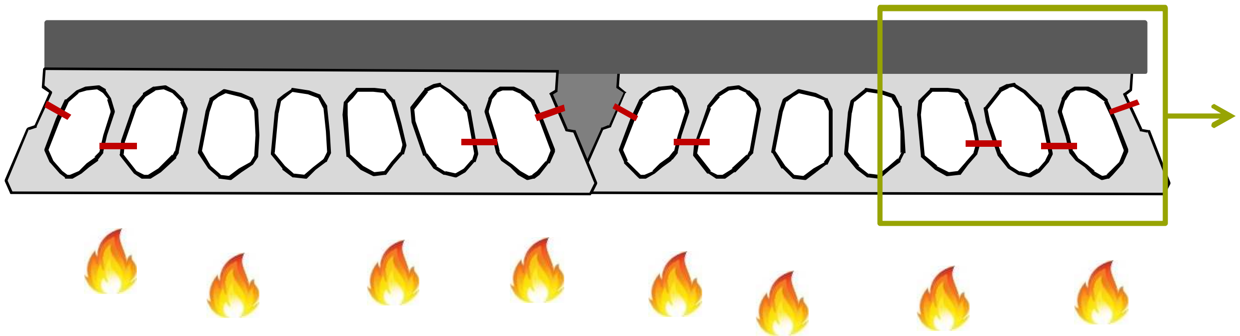


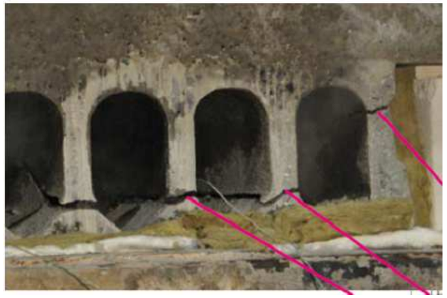
Risk of spalling due to blocking in HC floors

- Hinderance of expansion of the floor due to surrounding structure can lead to more local damage, which in general is not a problem

Blocking in floors – internal restraint

- Due to the thick (cold) topping the slab is internally partially or totally hindered to bend towards the fire
- Forces can occur after 30 minutes in the webs which can result in horizontal cracking of the webs.
  - Horizontal blocking is a decisive parameter
  - Drying shrinkage of the floor leading to shrinkage cracks can be enough to prevent the occurrence of horizontal web cracks
- Topping thickness should be limited to <u>25%</u> of the depth of the slab
  - This design rule is implemented in The Netherlands
  - This design rule is proposed in *fib* recommendations

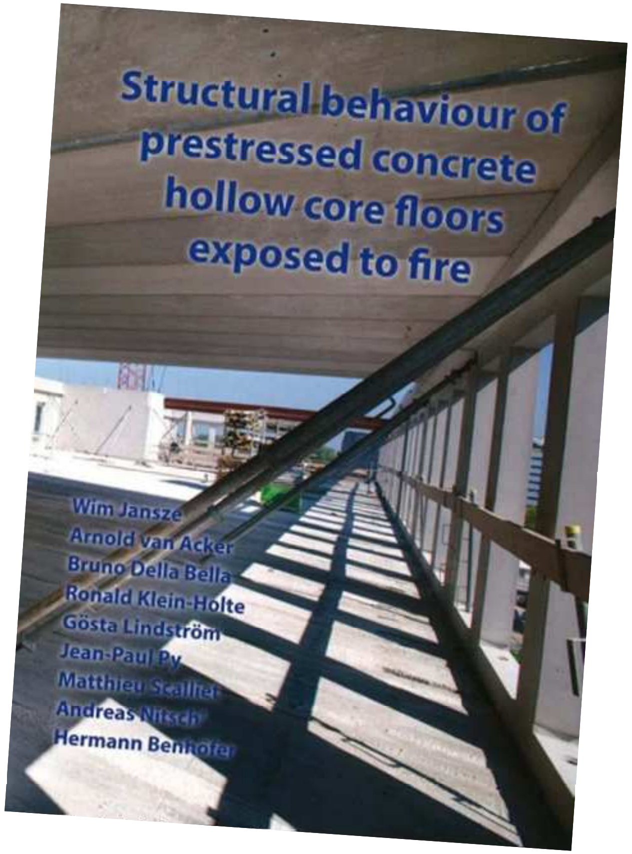




6. TO CONCLUDE

Fire resistance of hollowcore floors

- Every year around 20 to 25 million square metres of precast concrete hollow-core floors are erected in Europe. The estimated total stock of hollow-core floors currently installed in Europe is 1,000 million square meters.
- Experiences with past performance of hollow-core floors confirm that under fire conditions hollow-core floors have excellent fire resistance, confirmed in the Holcofire project:
  - The product meets regulations and requirements
  - The product performs well when exposed to fire
- In specific cases, fires in car parks are more severe than standard fires



THANKS FOR YOUR ATTENTION

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