INTERNATIONAL PRESTRESSED HOLLOWCORE ASSOCIATION

HOLCOFIRE

Behaviour of prestressed hollowcore floors exposed to fire

Shear resistance of hollow core slabs under fire validated with EN1168 Annex G

Jean-Paul Py

Overview of presentation

1. Introduction
2. EN1168 Annex G
3. Validation on 42 fire tests
4. Holcofire G tests
5. Conclusion

Structural floor calculations
ULS Bending

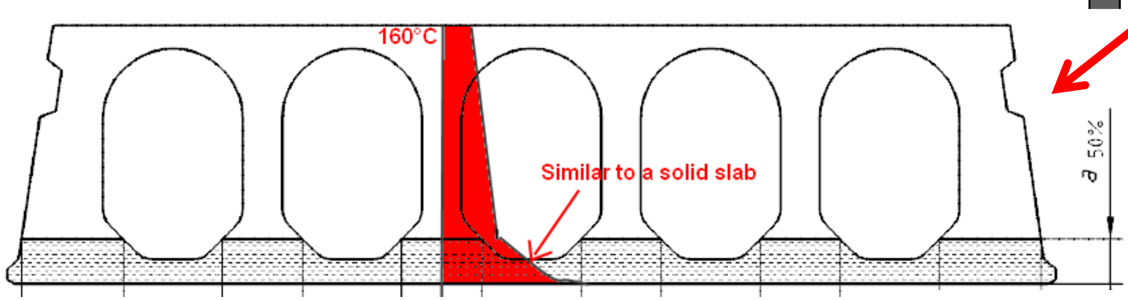
Cold

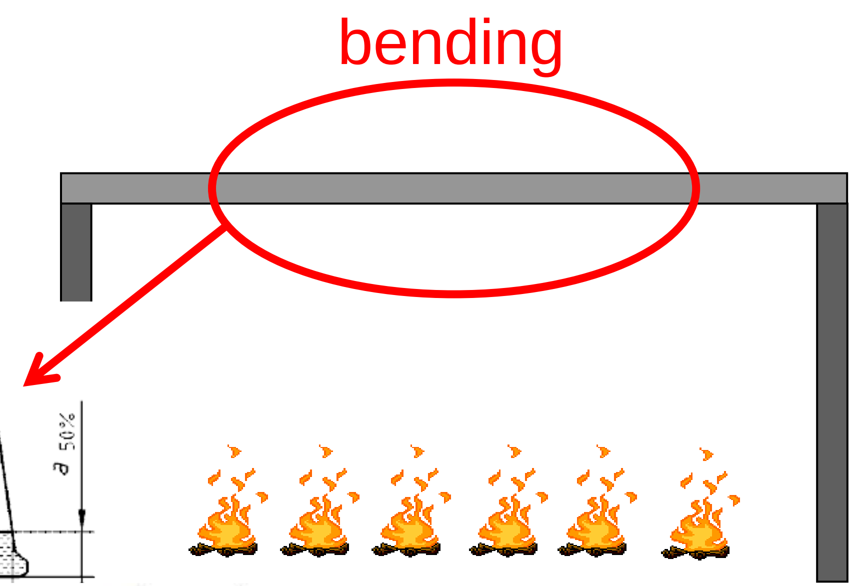
EN1992-1-1

Fire

EN1992-1-2 Bending

Temperature according G.1.2 –Annex G

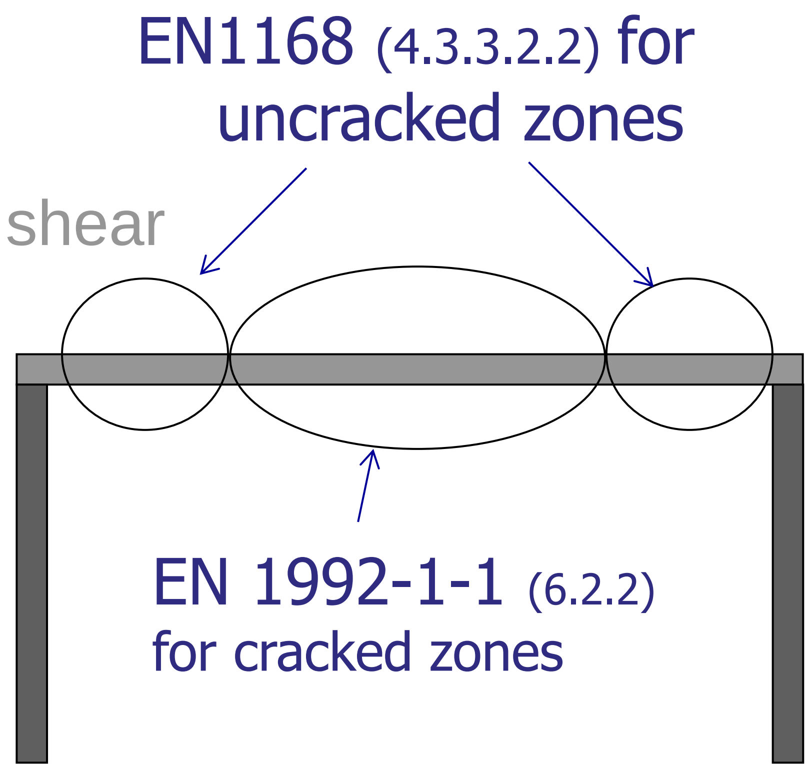




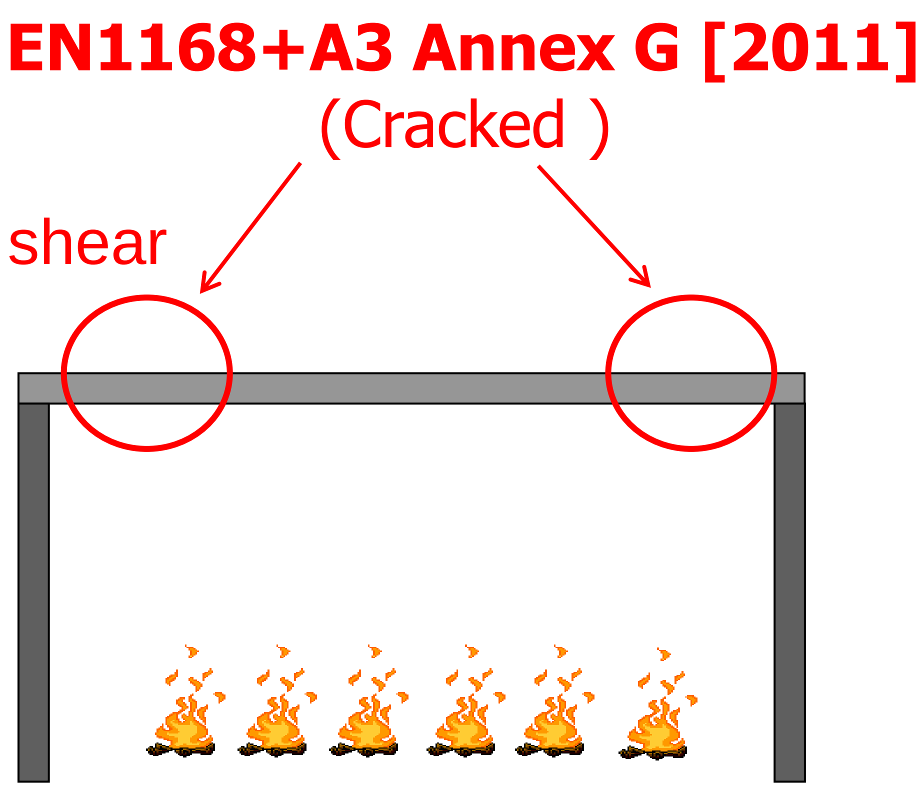
$a_{50\%}$ = level on which $\sum_{i=1}^{n} b_{w(i)} = \sum_{i=1}^{m} b_{c(i)}$

Structural floor calculations
ULS Shear

Cold



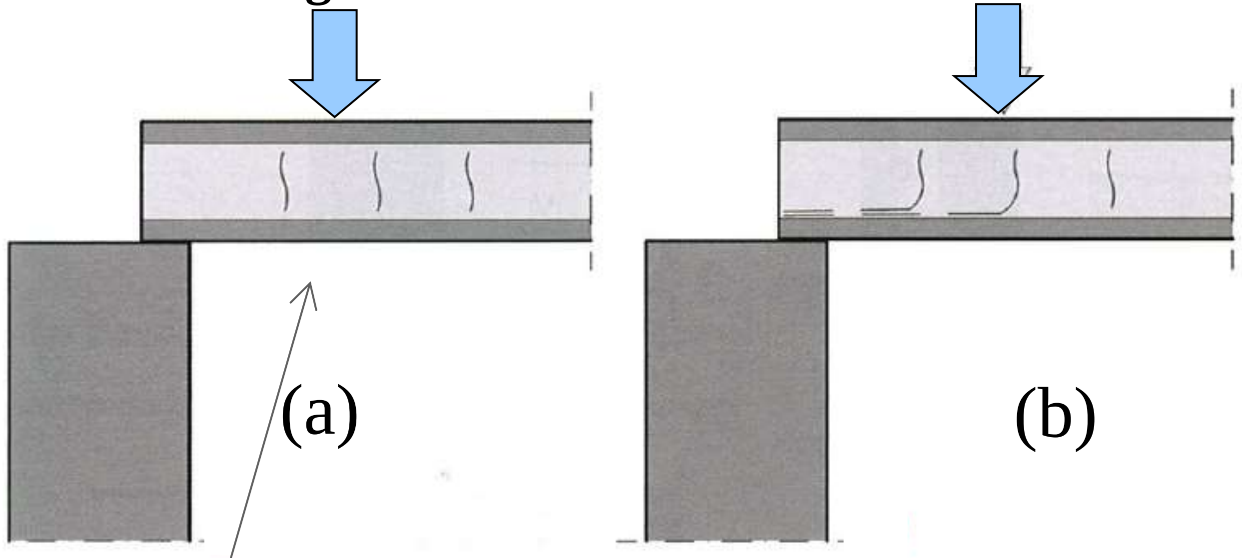
Fire



Postulated failure model

Vertical cracking due to **thermal eigen stresses**

Horizontal cracking at level of strand due to **shear stresses**

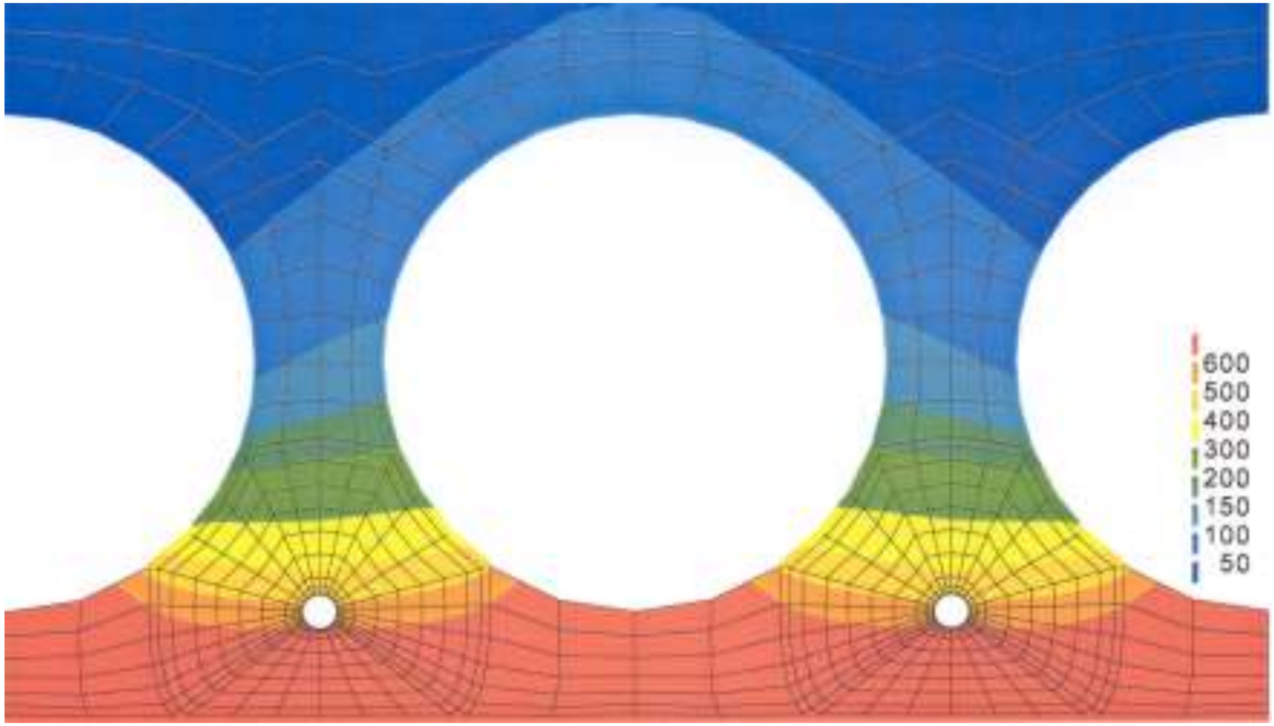


Tests Fellinger 2004

Tests G-series Holcofire

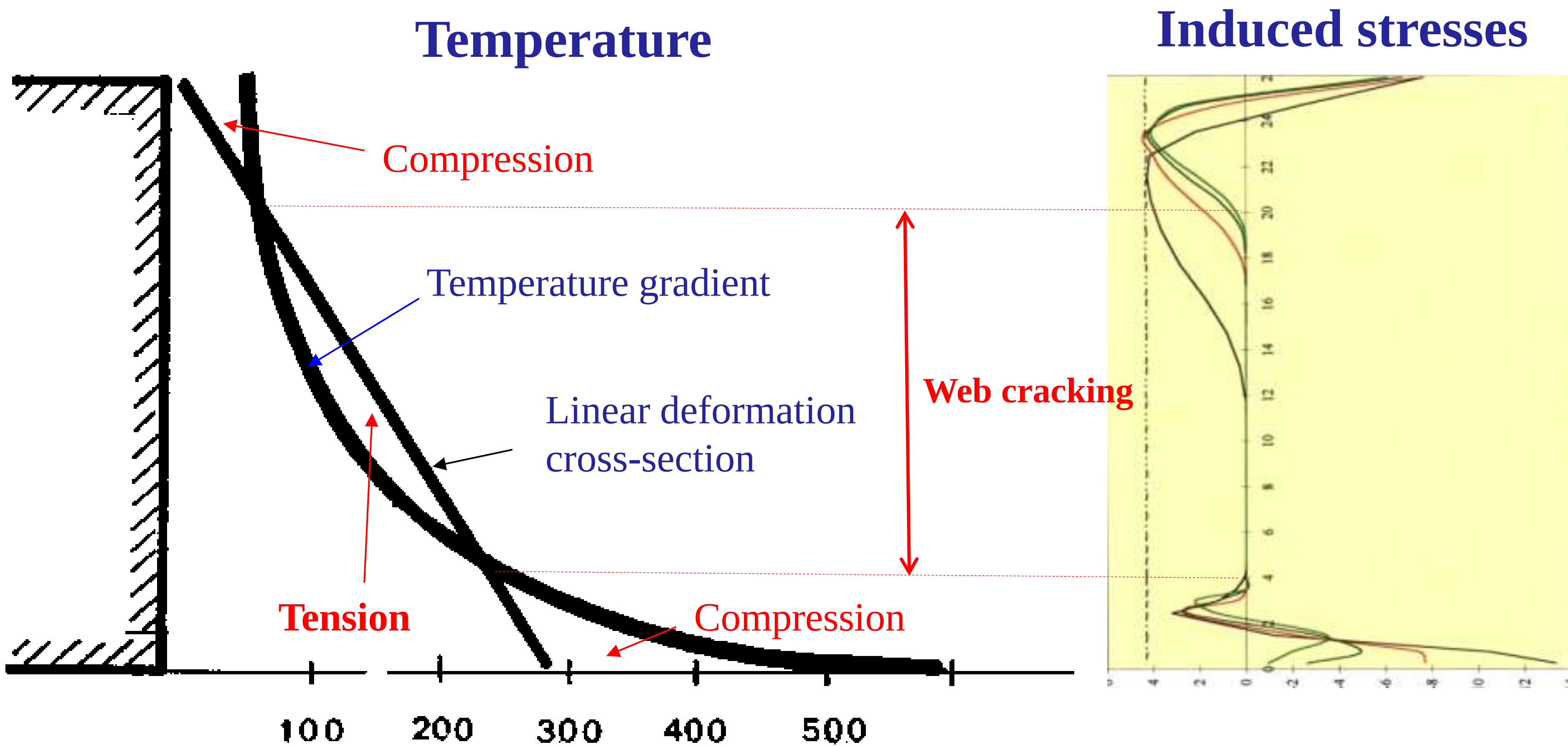
Induced thermal stresses

Origin of “Eigen stresses”



Temperature in the cross section

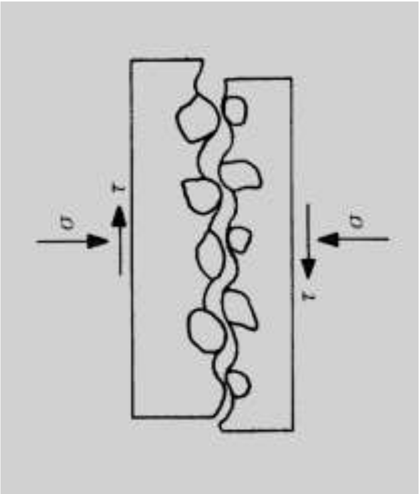
Induced thermal stresses
Origin of “Eigen stresses”



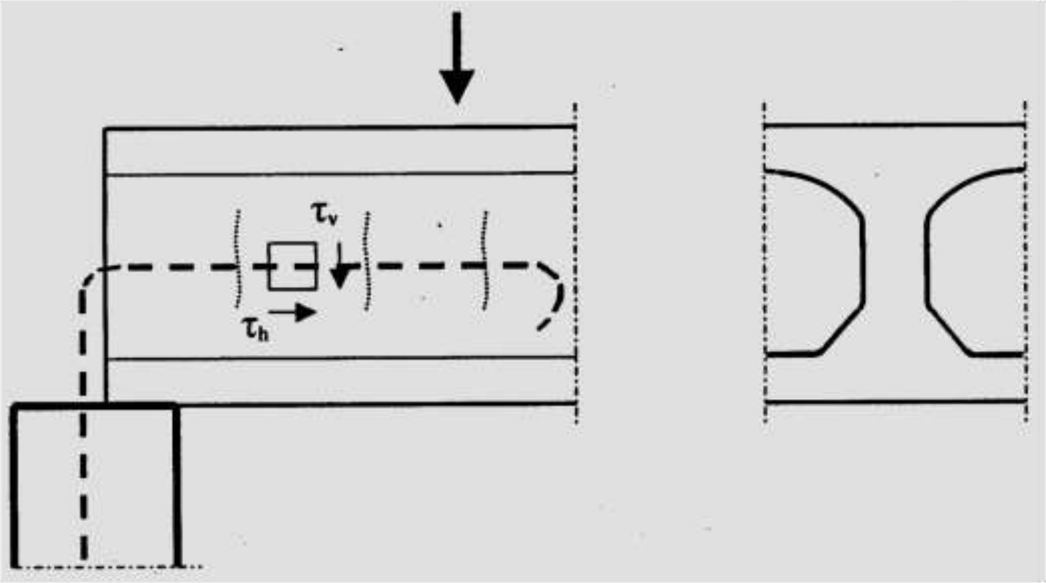
Internal stresses due to the incompatibility between non-linear temperature profile and linear deformation of the cross-section will induce vertical cracks in the web

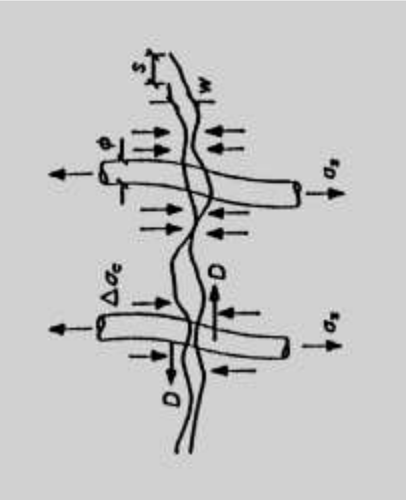
Shear capacity cracked concrete

- Shear transfer through cracks



aggregate interlock

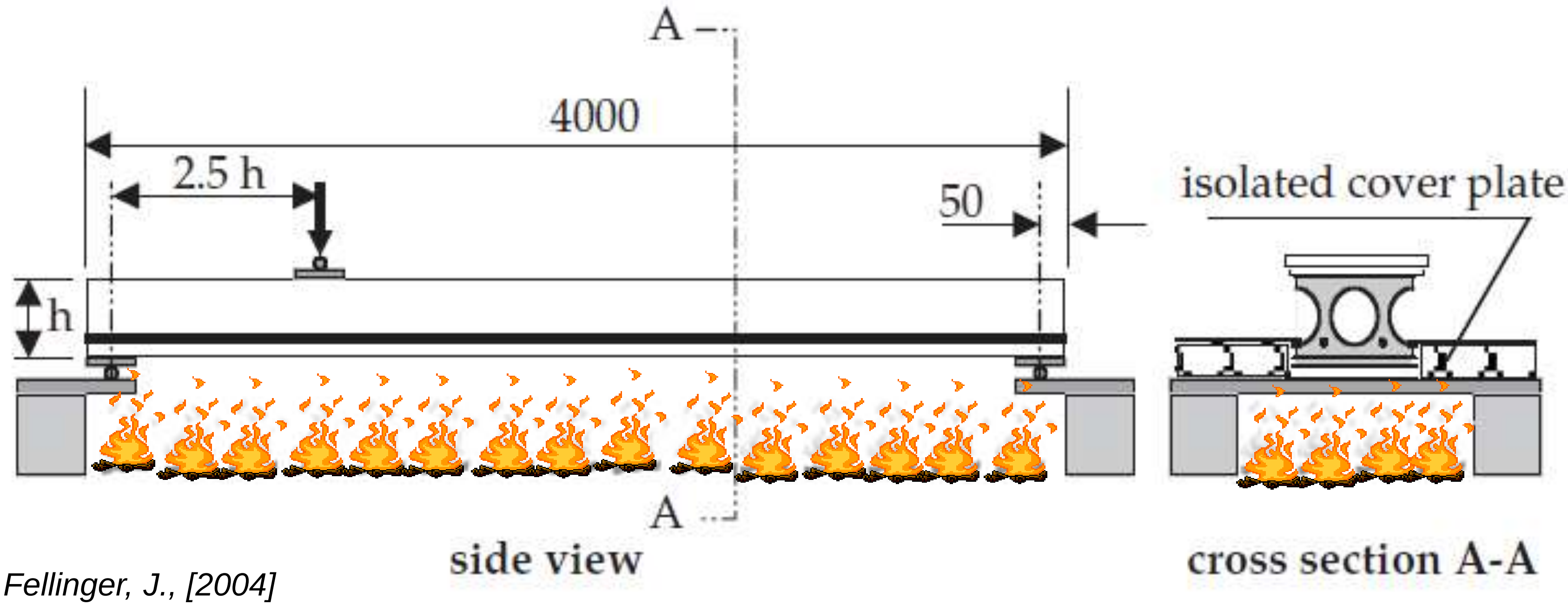




dowel effect

Cracked concrete sections are able to transfer shear through aggregate interlock on condition that the cracks remain closed

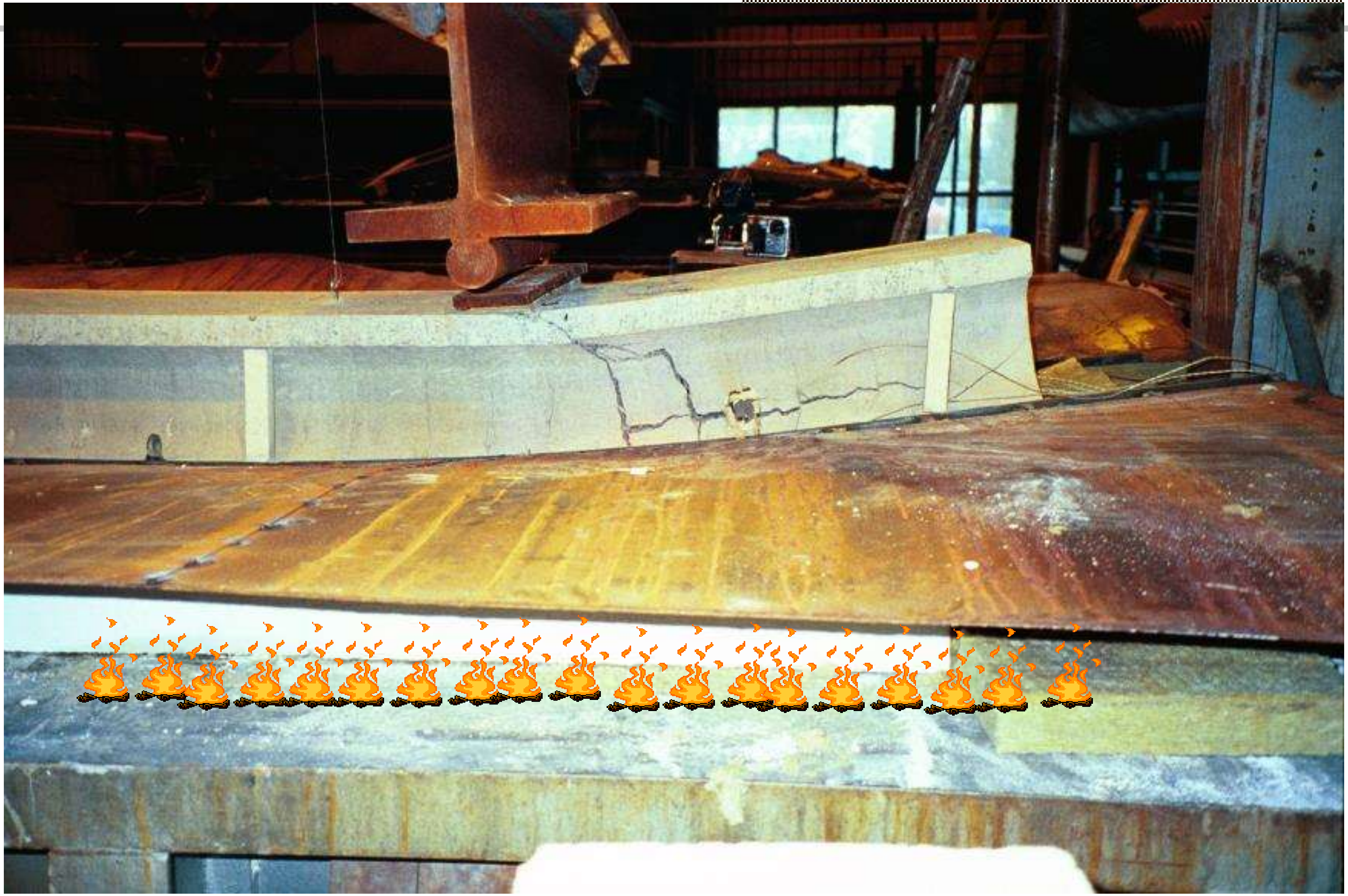
Fellinger fire test on double web element



Fellinger, J., [2004]

Fellinger test

123 minutes



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EN 1168+A3 Annex G – Calculation formula shear and anchorage capacity of HC exposed to fire

Empirical shear equation inspired from EN 1992-1-1 6.2a formula:

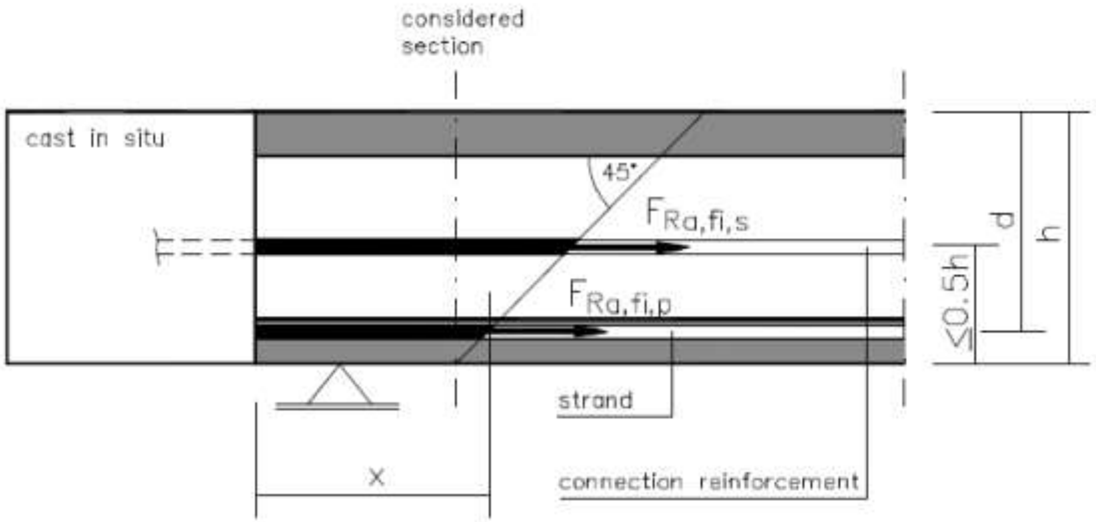
$$V_{Rd,c} = [C_{Rd,c}k(100\,\rho_l\,f_{ck})^{1/3} + k_1\,\sigma_{cp}]\,b_w d$$

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

$$C_{\theta.1} = 0.15 \cdot \min(k_p(\theta_p)\sigma_{cp,20^\circ C}; \frac{F_{R,a,fi,p}}{A_c})$$

$$\alpha_k = 1 + \sqrt{\frac{200}{d}} \leq 2{,}0$$

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



$C_{\theta.1}$	Coefficient accounting for concrete stress under fire conditions
$k_{p(\theta p)}$	Strength reduction factor for the prestressing steel (EN 1992-1-2 clause 4.2.4.3.)
$\sigma_{cp,20°C}$	Average concrete stress due to prestressing at normal temperature
A_c	Concrete section area
$F_{R,a,fi,p}$	Force capacity of prestressing steel anchored in considered cross section
$C_{\theta.2}$	Coefficient accounting for anchored longitudinal reinforcement:
$F_{R,a,fi}$	Force capacity of prestress and reinforcement anchored in considered cross section
f_{yk}	Characteristic yield strength of the reinforcement
$f_{c.fi.m}$	Average strength of concrete at elevated temperature, fc,fi,m
b_w	Total web thickness of the hollow core slab
d	Effective depth at ambient temperature

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3. **Validation on 42 fire tests**
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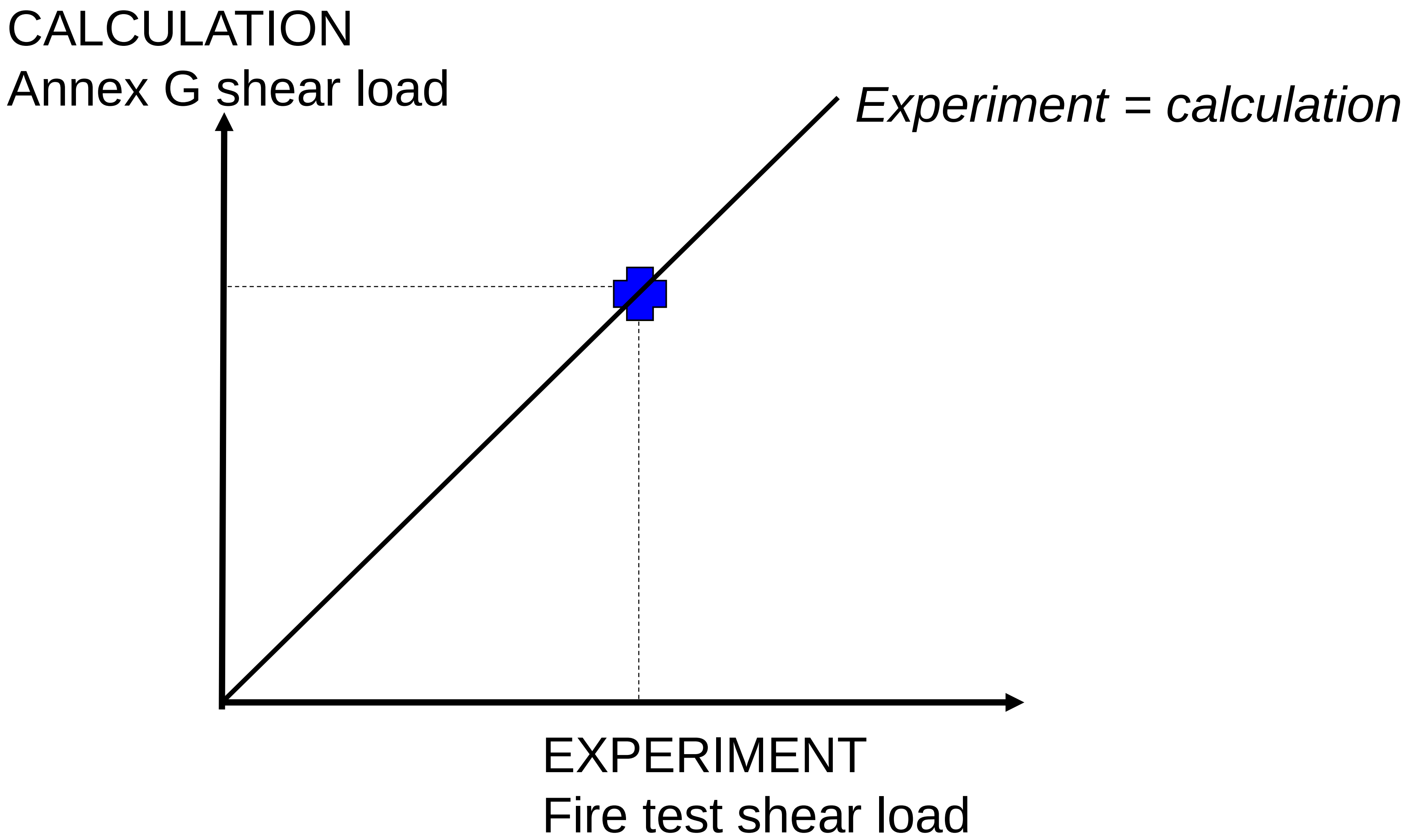
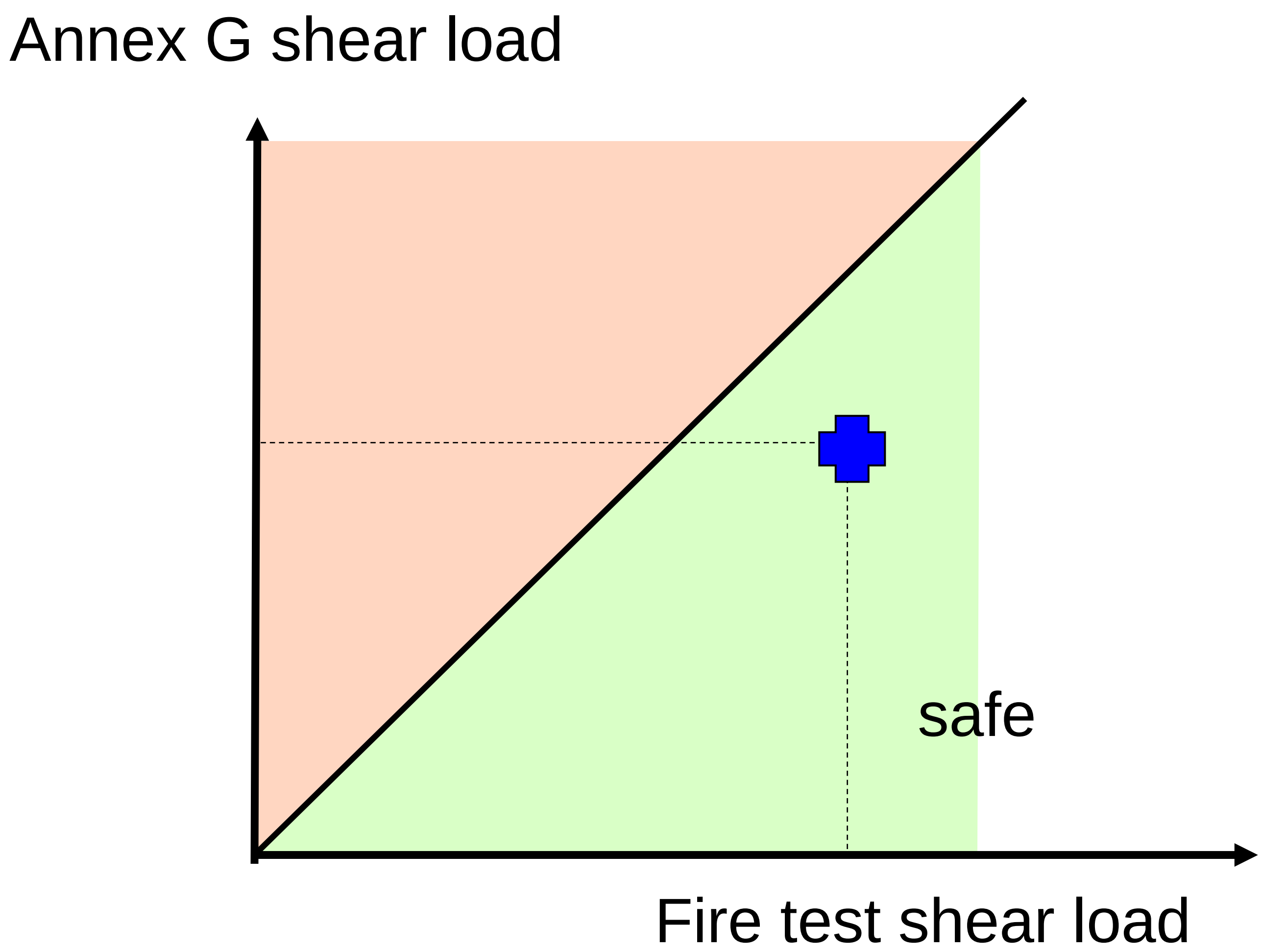
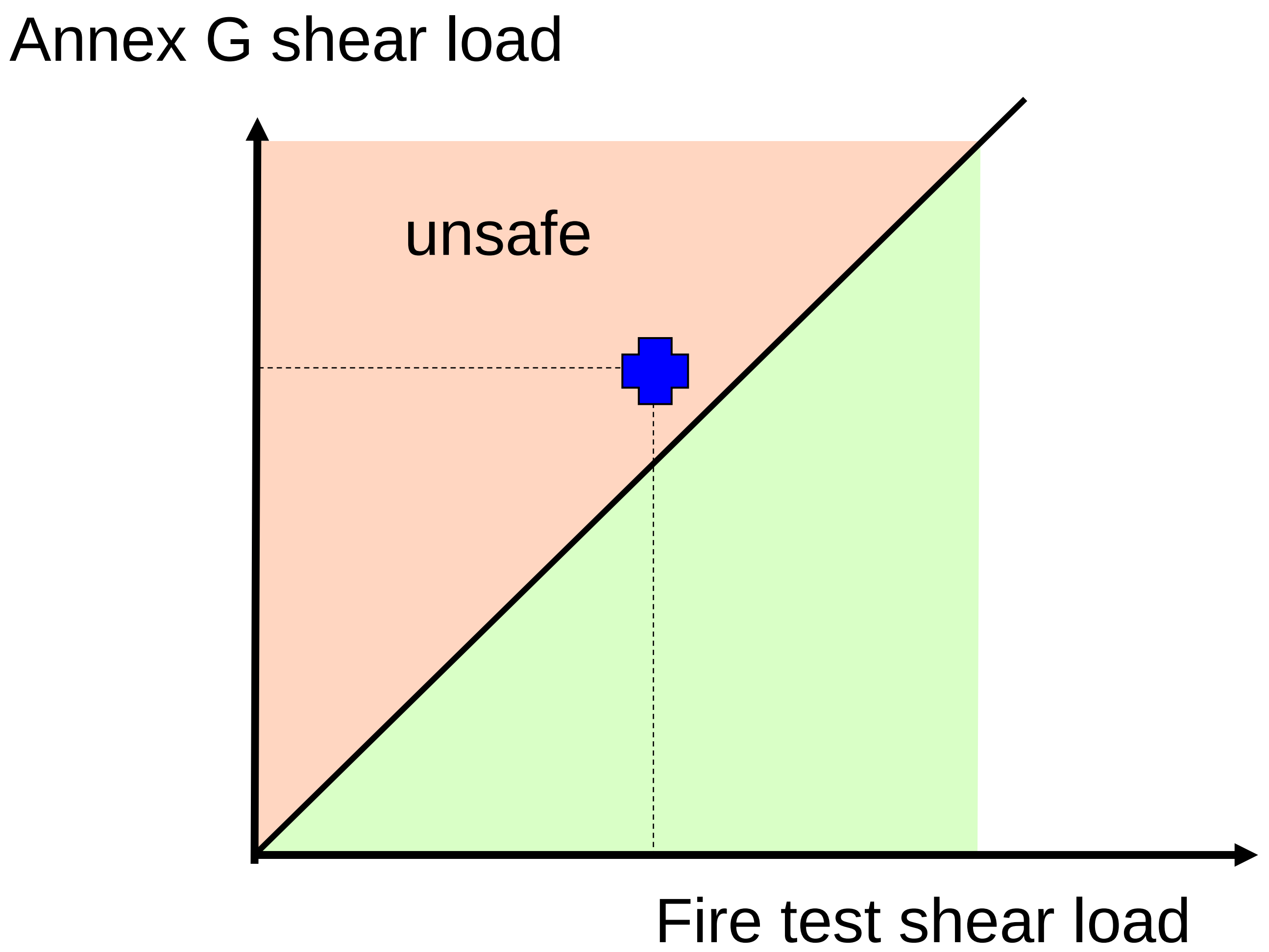
Validation of Annex G - theory



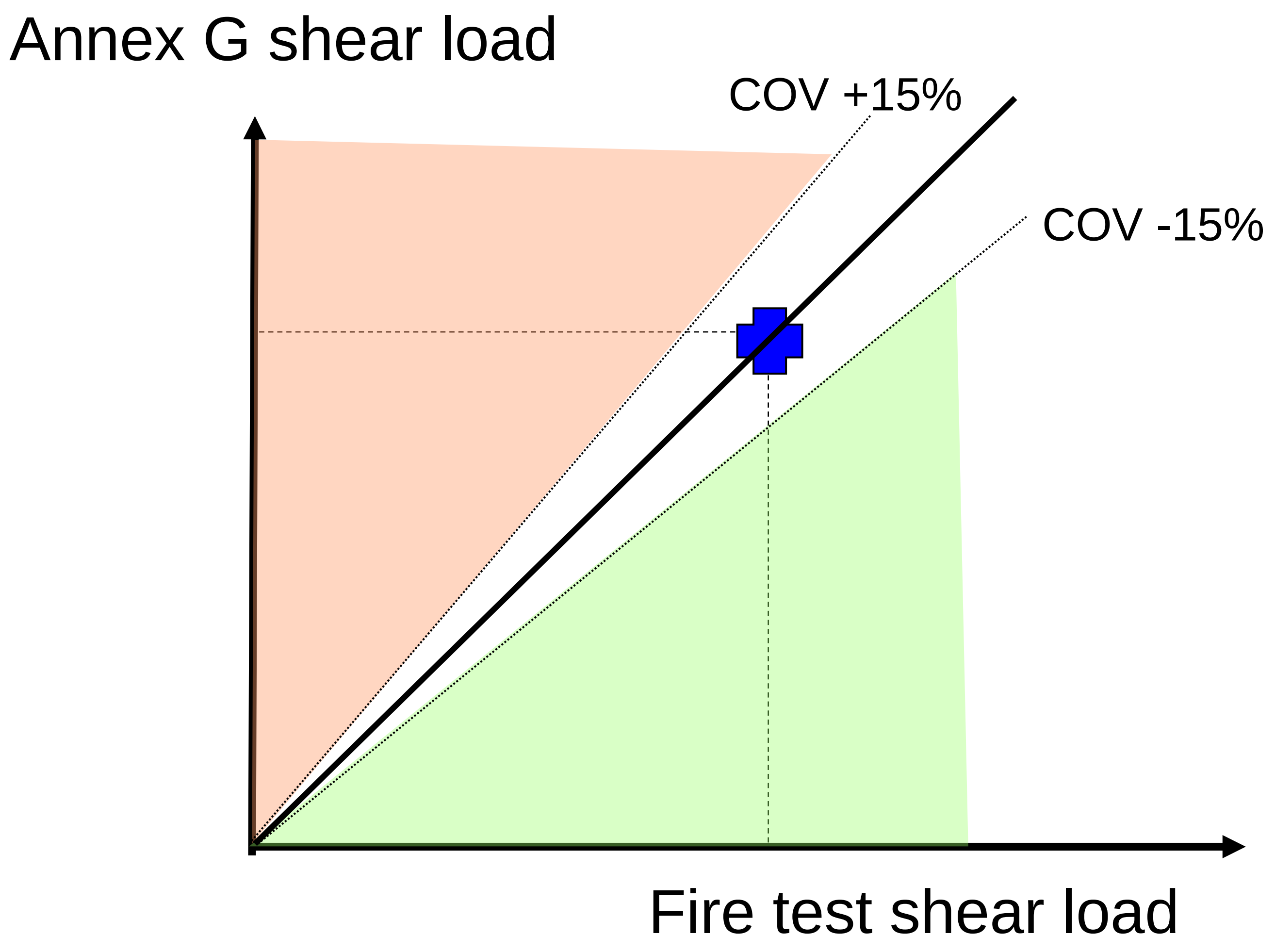
Validation of Annex G - theory



Validation of Annex G - theory

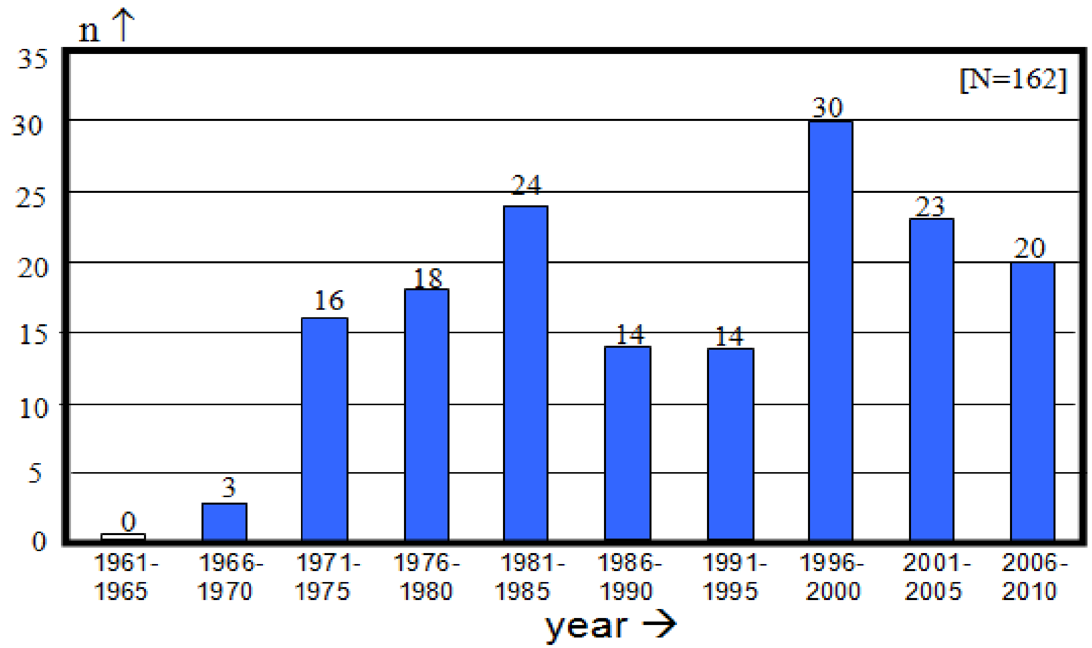


Validation of Annex G - theory



Holcofire database

- Database with **162** fire test results
- Period 1966-2010



42 fire tests shear and anchorage failure

- **in 20 fire tests the slabs failed unexpectedly and prematurely in shear ;**
- **in 22 fire tests the set-up was designed to fail in shear during the fire test (or loaded afterwards to shear failure).**

42 fire tests from database (1 of 2)

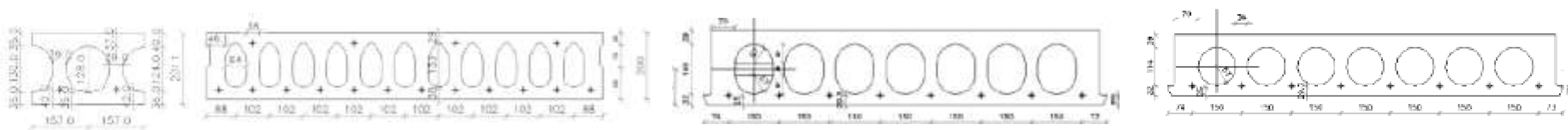
H#	Test ID	Slab Depth [mm]	Slab Width [mm]	Top-ping [mm]	Strands per slab width [-]	Webs Unit System	Objective to fail in test/ Premature failure
H7	RUG 943 element I [1971]	265	1200	0	6ø12.5	Unit	No / Yes
H8	RUG 943 element II [1971]	265	1200	0	6ø12.5	Unit	No / Yes
H9	RUG 943 element III [1971]	265	1200	0	6ø12.5	Unit	No / Yes
H39	VTT PAL 2480 [1982]	275	1200	0	6ø12.5	Unit	No / Yes
H45	VTT PAL 4248 [1984]	265	2400	0	8ø12.5	System	No / Yes
H48	VTT PAL 4450 [1984]	265	1200	0	6ø9.3	System	No / Yes
H58	VTT PAL 566d [1985]	265	1200	0	6ø12.5	System	No / Yes
H73	VTT PAL 90228 [1990]	265	1200	0	6ø12.5/4ø9.3	System	No / Yes
H83	EMPA B2-2 [1995]	200	1200	0	12ø9.3	System	No / Yes
H85	EMPA B2-4 PL [1995]	200	1200	0	12ø9.3	System	No / Yes
H86	EMPA B3-1 [1995]	200	1200	0	12ø9.3	System	No / Yes
H96	DIFT X52650d [1998]	185	1200	0	8ø9.3	Unit	No / Yes
H97	DIFT X52650e [1998]	220	1200	0	8ø9.3	Unit	No / Yes
H98	DIFT X52650f [1998]	270	1200	0	4ø15.2/4ø12.5	Unit	No / Yes
H102	RUG 9158 [1999]	265	1200	30	10ø9.3	System	No / No
H104	TNO R-A200 [1999]	200	314	0	2ø9.3	2-webs	Yes / Yes
H106	TNO R-XB200 [1999]	200	316	0	2ø9.3	2-webs	Yes / No
H107	TNO R-VX265 [1999]	275	444	0	2ø12.5	2-webs	Yes / Yes
H108	TNO R-K400 [1999]	400	561	0	4ø12.5 - 4ø9.3	2-webs	Yes / Yes
H111	TNO R-K400-R [1999]	400	582	0	4ø12.5 - 4ø9.3	2-webs	Yes / Yes
H112	TNO R-K400-F [1999]	400	570	0	4ø12.5 - 4ø9.3	2-webs	Yes / Yes
H114	TNO U-VX265 [1999]	265	1200	0	6ø12.5	Unit	Yes / Yes
H115	TNO U-HVP260A-1 [2000]	260	1200	0	6ø12.5	Unit	Yes / Yes

42 fire tests from database (2 of 2)

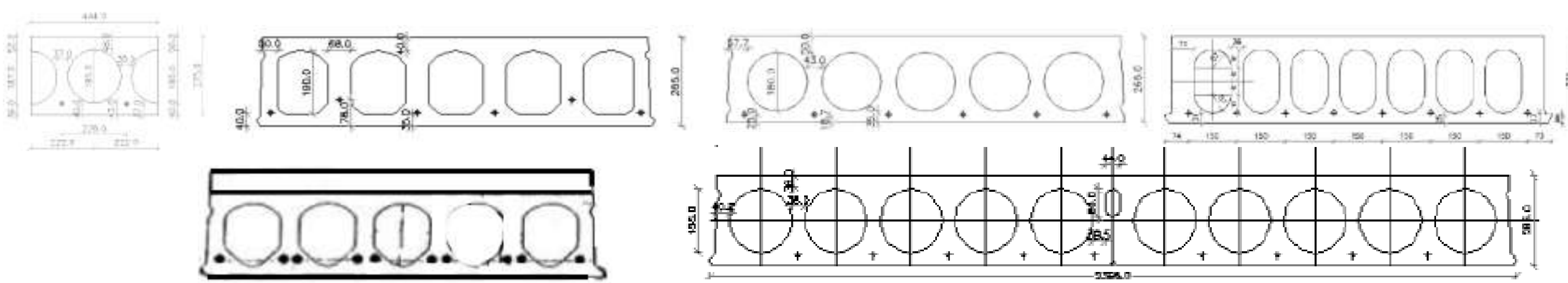
H#	Test ID	Slab Depth [mm]	Slab Width [mm]	Top-ping [mm]	Strands per slab width [-]	Webs Unit System	Objective to fail in test/ Premature failure
H116	TNO U-HVP260A-2 [2000]	260	1200	0	6ø12.5	Unit	Yes / Yes
H117	TNO U-HVP260A-3 [2000]	260	1200	0	6ø12.5	Unit	Yes / Yes
H118	TNO U-K400 [2000]	400	1200	0	8ø12.5/8ø9.3	Unit	Yes / Yes
H119	TNO R-HVP260A23 [1999]	255	445	0	2ø12.5	2-webs	Yes / Yes
H120	TNO R-HVP260A20 [2001]	260	440	0	2ø12.5	2-webs	Yes / Yes
H121	TNO R-HVP260A17 [2001]	260	448	0	2ø12.5	2-webs	Yes / Yes
H122	TNO R-HVP260A14 [2001]	260	446	0	2ø12.5	2-webs	Yes / Yes
H123	TNO R-HVP260S23 [2001]	260	444	0	2ø12.5	2-webs	Yes / Yes
H124	TNO R-HVP260S17 [2001]	260	444	0	2ø12.5	2-webs	Yes / Yes
H125	TNO R-HVP260S11 [2001]	260	444	0	2ø12.5	2-webs	Yes / No
H126	TNO R-HVP260A23F [2001]	260	444	0	2ø12.5	2-webs	Yes / Yes
H127	TNO R-HVP260A20F [2001	260	444	0	2ø12.5	2-webs	Yes / Yes
H128	TNO R-HVP260A17F [2001	260	444	0	2ø12.5	2-webs	Yes / Yes
H130	ITB LP 534.2 [2001]	265	1200	50	10ø12.5	System	No / Yes
H131	ITB LP 534.3 [2002]	265	1200	50	6ø12.5	System	No / Yes
H132	ITB test 1 (F.18.1)	200	1200	0	6Ø9.7	System	No / Yes
H133	ITB test 4 (F.19.1)	270	1200	50	7Ø12.5	System	No / Yes
H138	DIFT DCPA [2004] (F.22)	265	1200	0	10ø12.5	System	No / Yes
H142	SPTRI P502076 SP3 [2005]	265	1200	0	10ø12.5	System	Yes / Yes
		255-275 = 30x 185-220 = 8x 400 = 4x				2-webs = 16x Unit = 12x System = 14x	

Cross sections in 42 fire tests

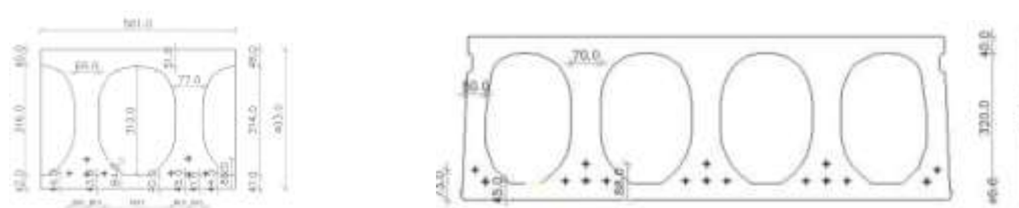
- **Slab depth 185 to 220 mm → 8x**



- **Slab depth 255 to 275 mm → 30x**



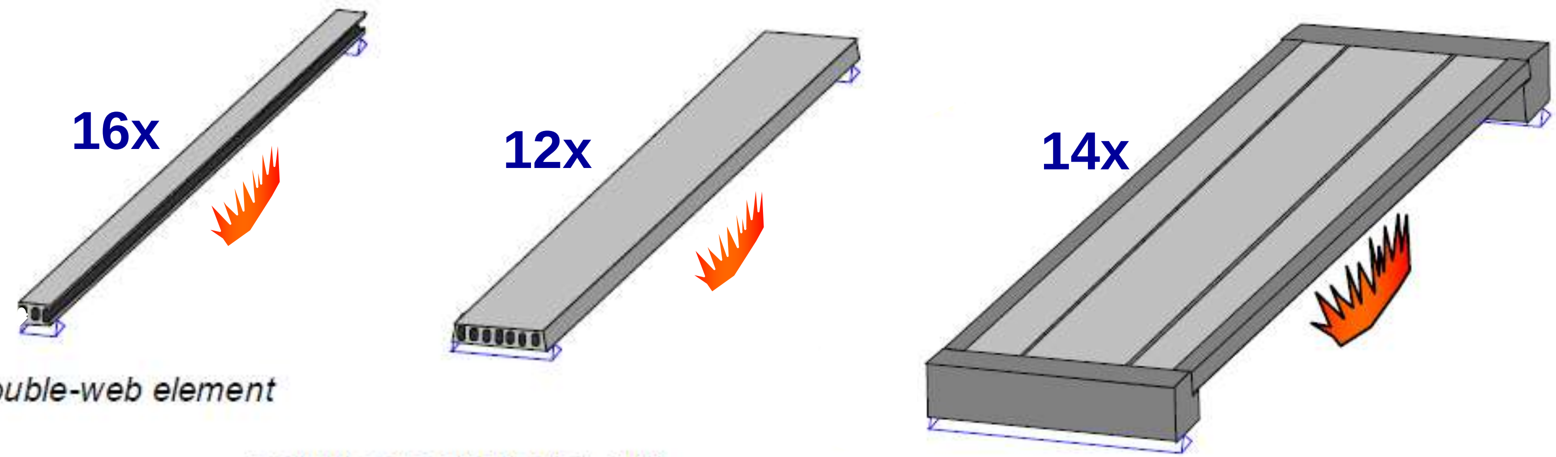
- **Slab depth 400 mm → 4x**



Test set-up in 42 fire tests

3 different types of test set-ups

Test set-up principles

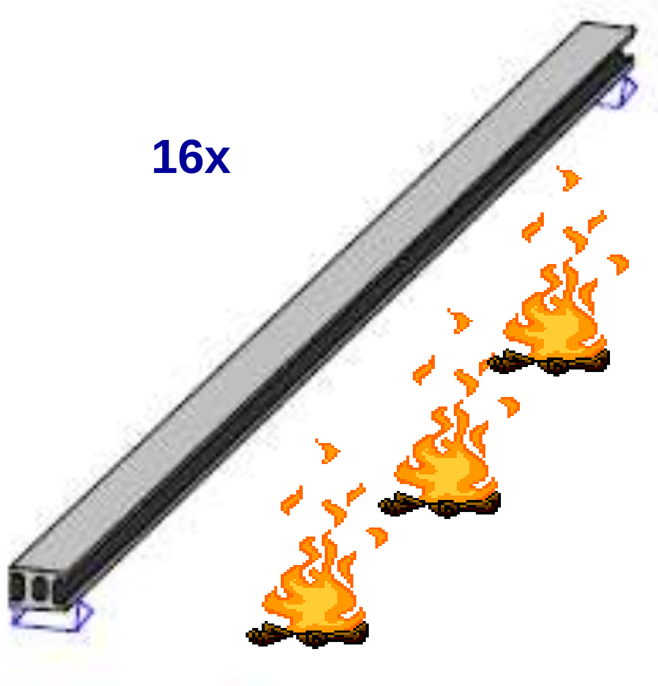


hollow core double-web element

hollow core single slab unit

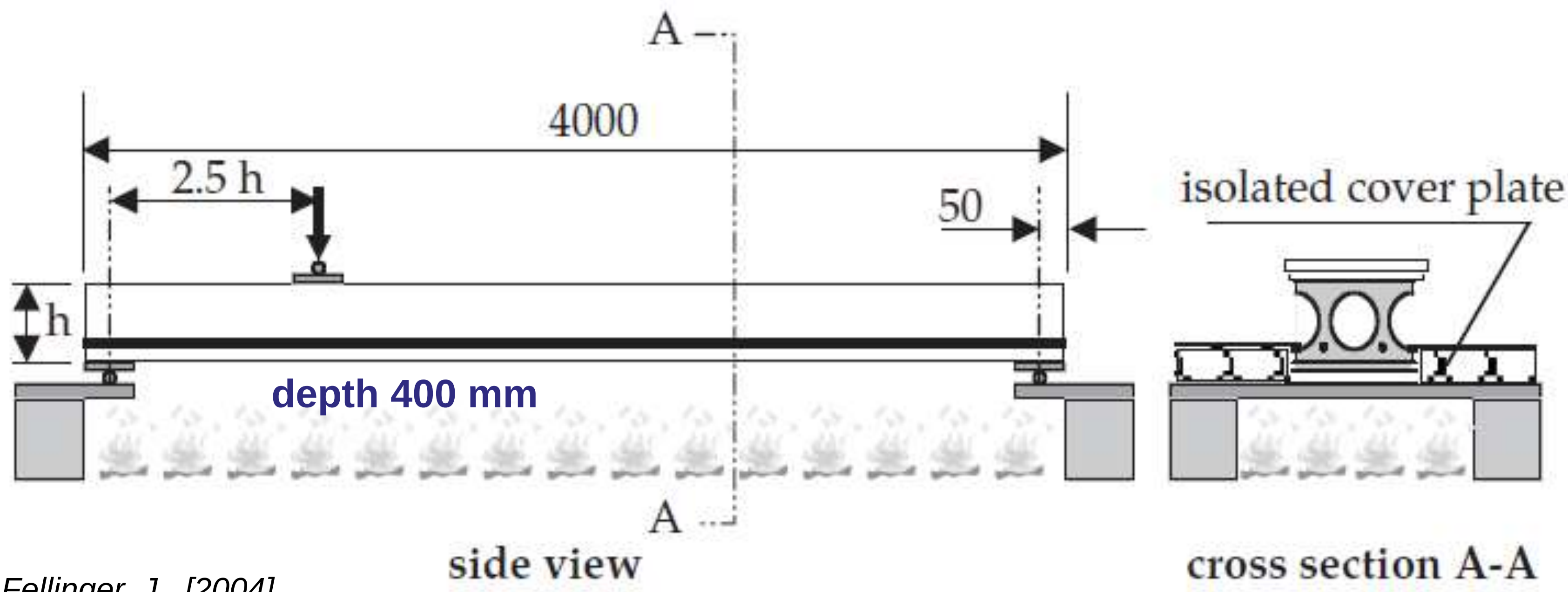
hollow core floor system
[EN1363-1 / EN1365-2]

Test set-up: double web element



Test set-up: double web element

H108 - Shear failure after 60 minutes in fire test

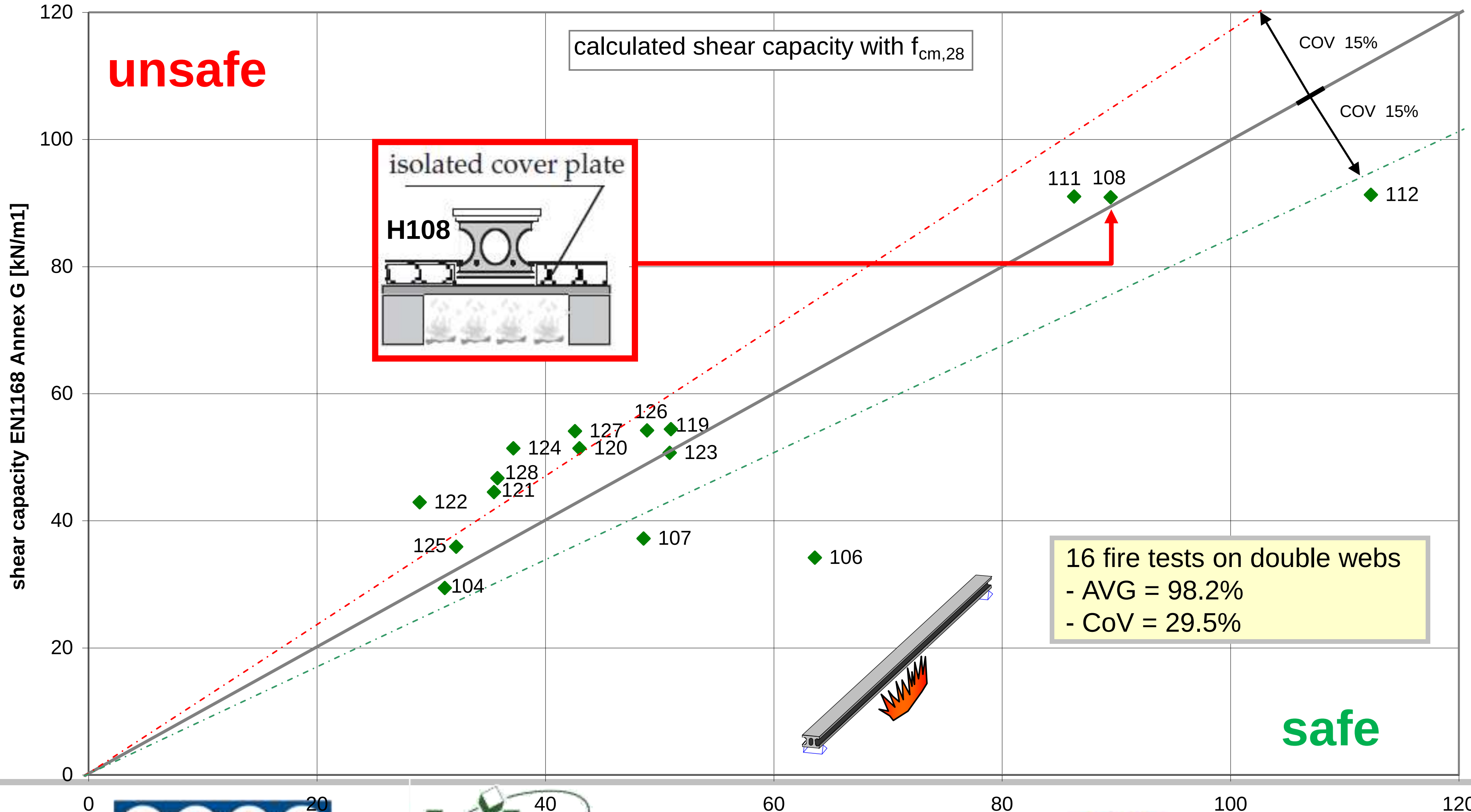


Fellinger, J., [2004]

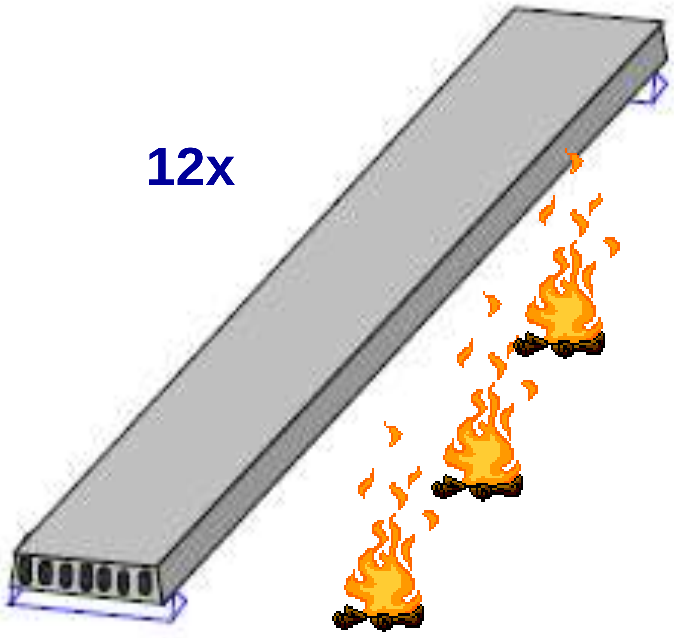
shear load in fire test = 89.5 kN/m
EN1168 Annex G capacity = 90.9 kN/m ➔ test / EN1168 = **98.5%**

Double webs element - 16 fire tests

Shear capacity from fire tests averages **98.2%** of EN1168+A3 Annex G

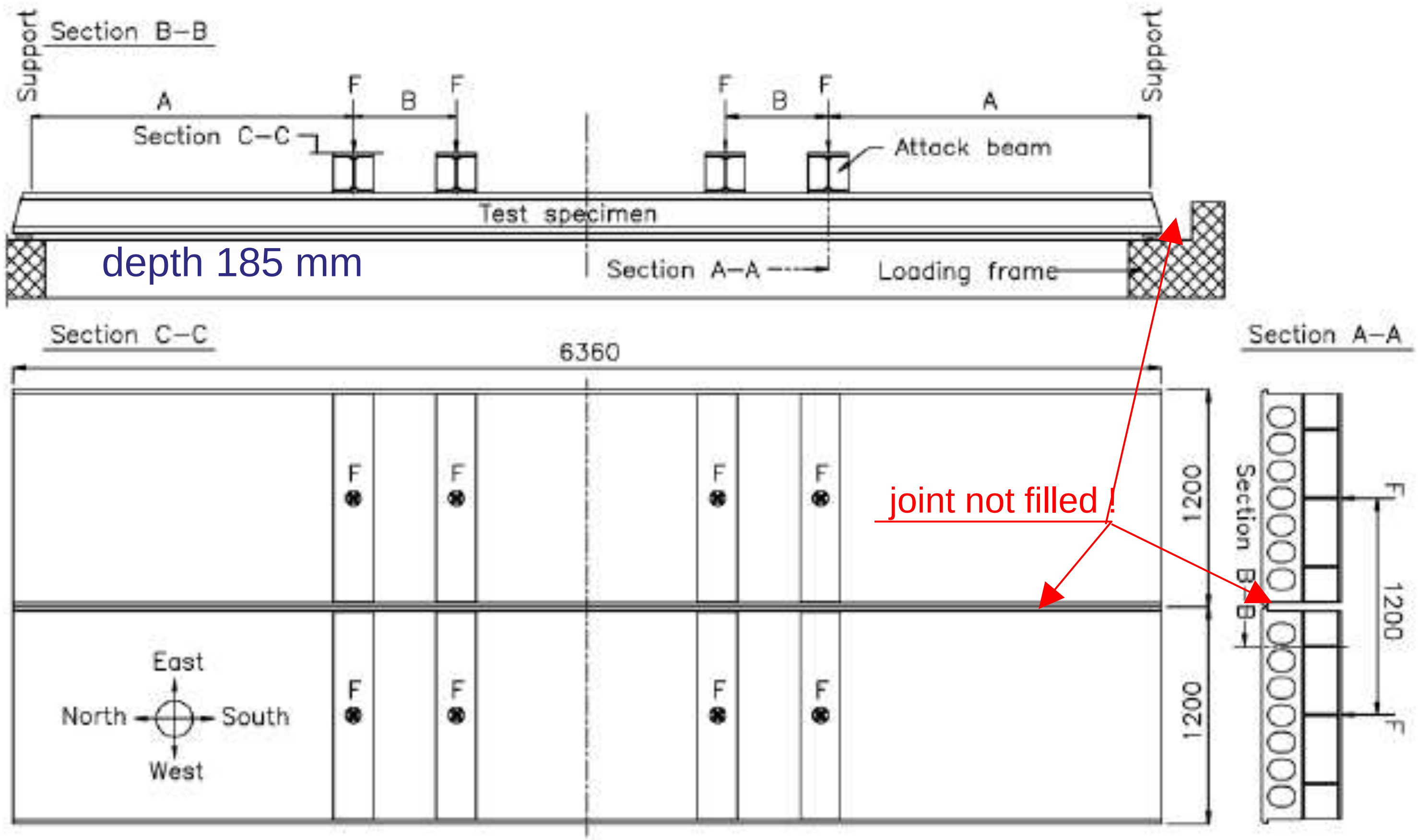


Test set-up: single slab unit



Test set-up: single slab unit

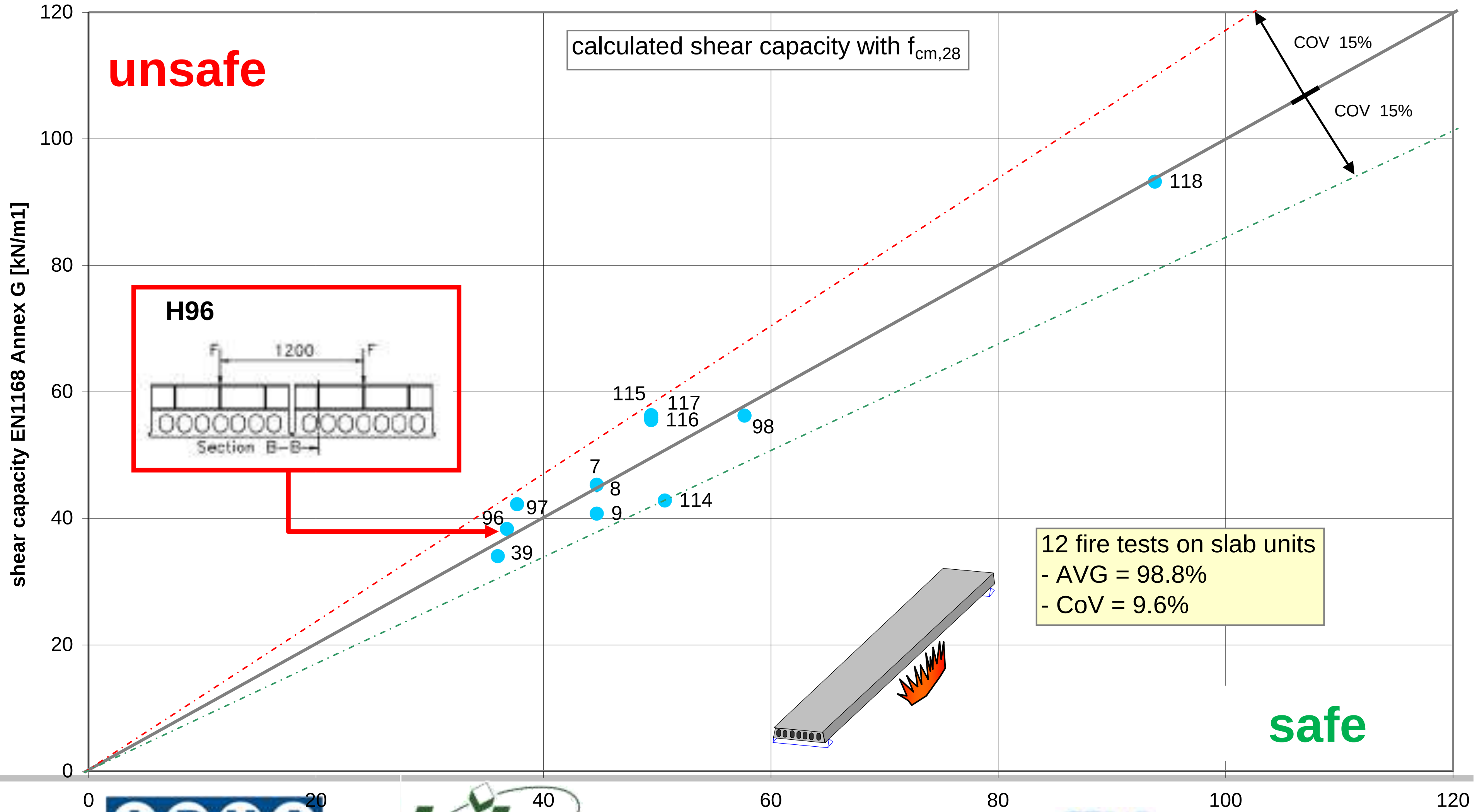
H96 - Shear failure after 21 minutes in fire test



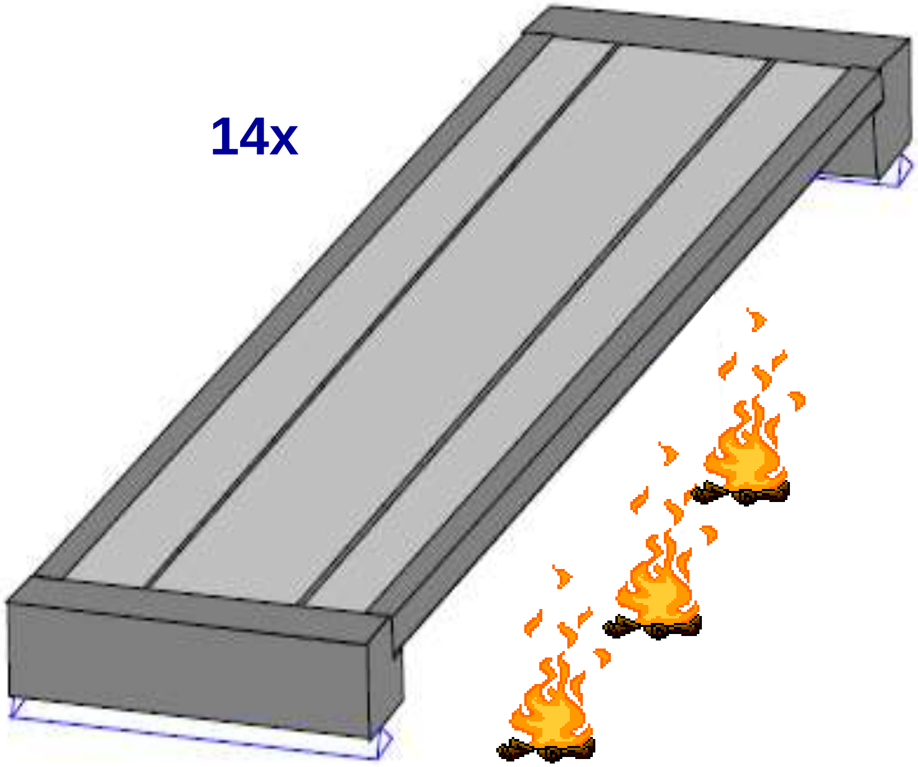
shear load in fire test = 36.8 kN/m
EN1168 Annex G capacity = 38.3 kN/m ➔ test / EN1168 = **96.1%**

Single slab unit - 12 fire tests

Shear capacity from fire tests averages **98.8%** of EN1168+A3 Annex G

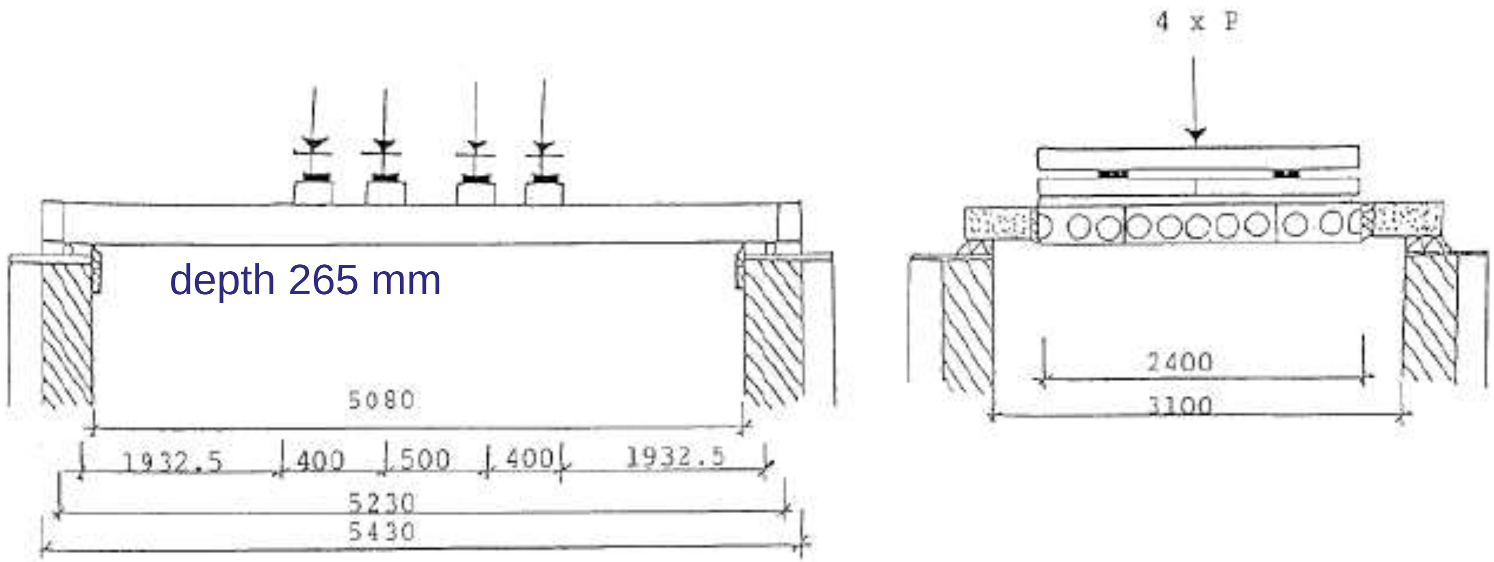


Test set-up: floor system



Test set-up: floor system

H58 - Shear failure after 77 minutes in fire test

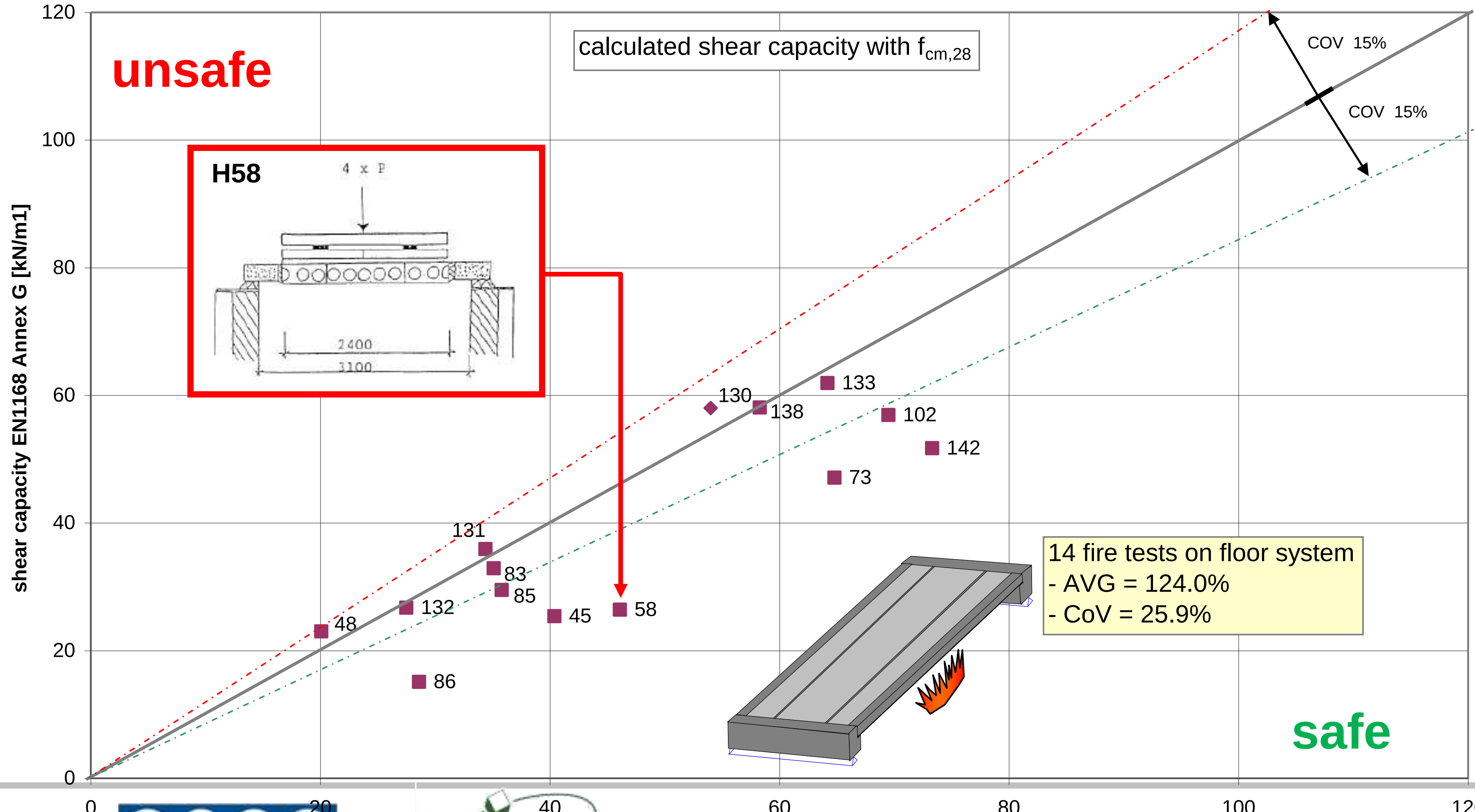


Hietanen, T. [1992]

shear load in test = 46.1 kN/m
Annex G capacity = 26.4 kN/m → test / EN1168 = **174.6%**

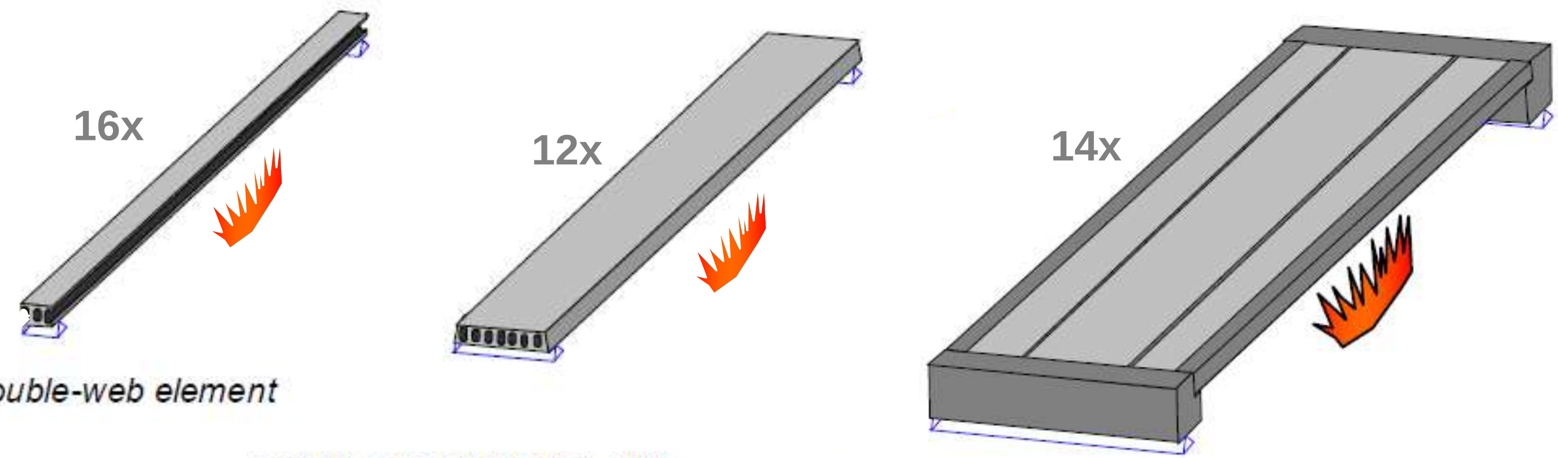
Floor system - 14 fire tests

Shear capacity from fire tests averages **124.0%** of EN1168+A3 Annex G



Validation of EN1168:A3 Annex G with 42 fire tests conducted 1966-2010

Test set-up principles



hollow core double-web element

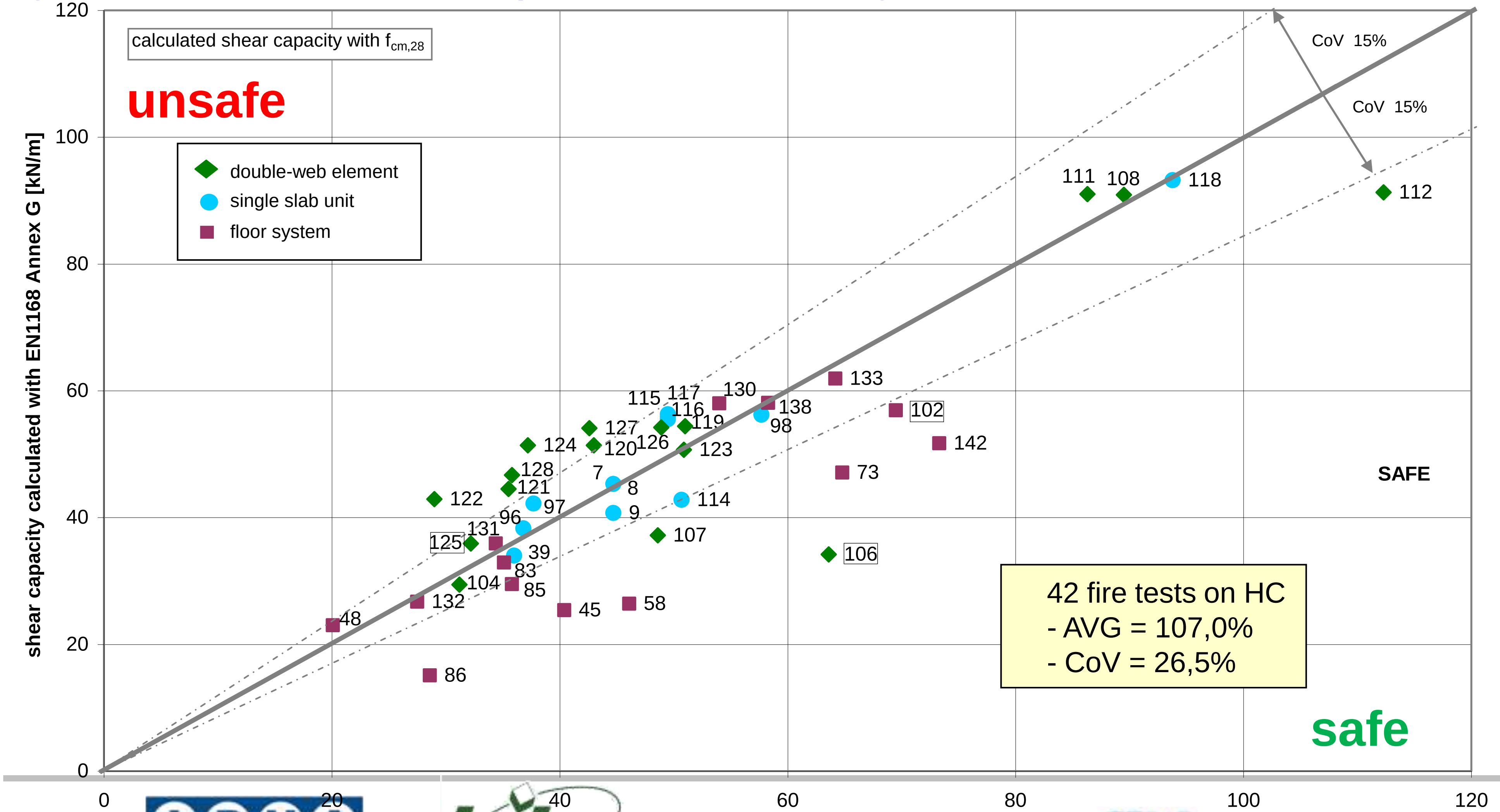
hollow core single slab unit

hollow core floor system
[EN1363-1 / EN1365-2]

Applied depth of hollowcore in fire tests: from 185 mm to 400 mm
185-220 mm → 8x / 255-275 mm → 30x / 400 mm → 4x

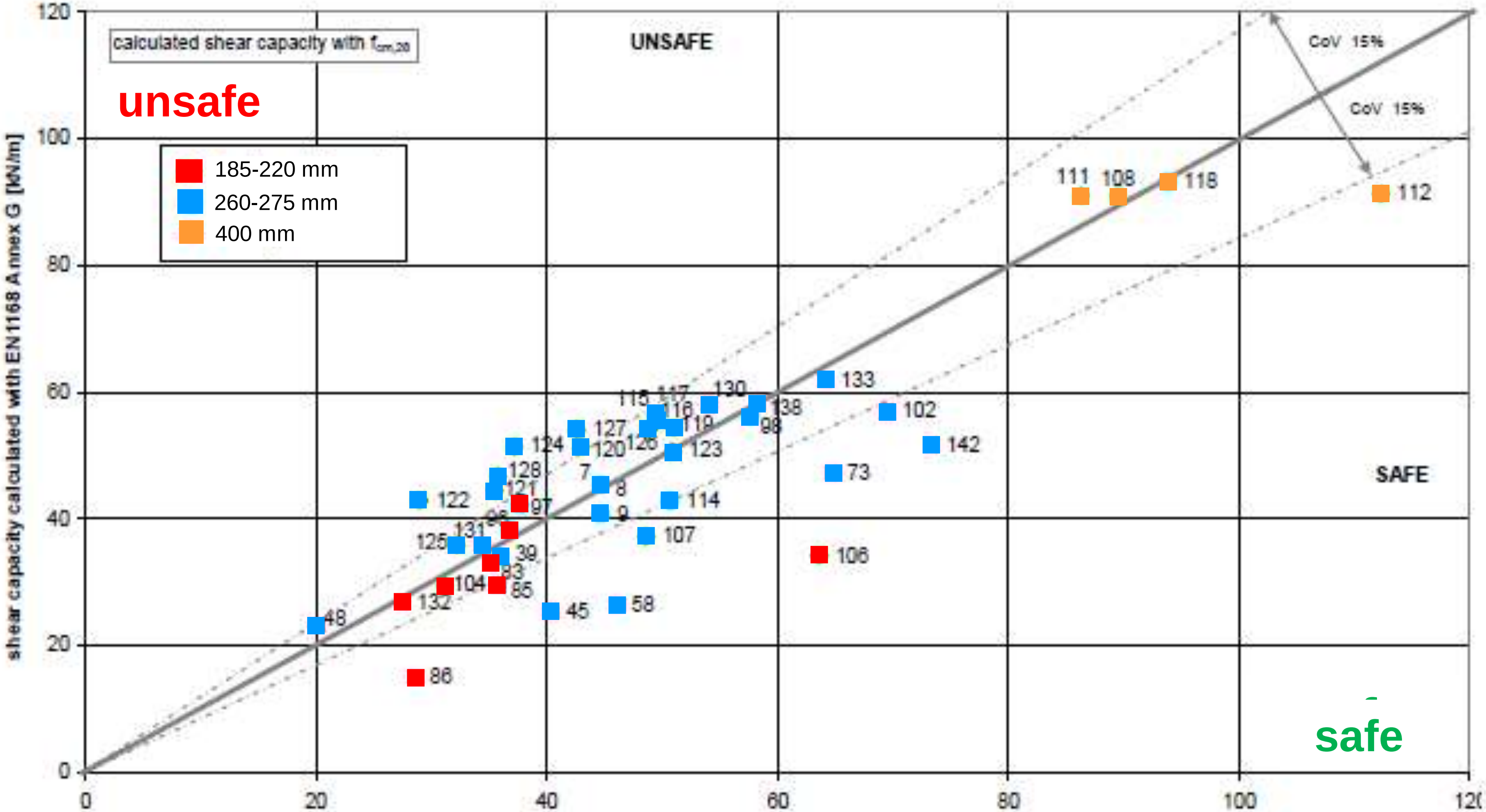
All 42 fire tests on hollow cores

Shear and anchorage capacities from fire tests are on average 7.0% higher than calculated capacities according to EN1168+A3 Annex G



Depth of hollowcore slabs [n=42]

EN1168:A3 Annex G is applicable for all hollow core slab depths covered by EN1168



Parameters in EN1168 Annex G

Outcome variation when an individual parameter is changed ± 20% Example case: VTT 4450 [1984] at 60 minutes		
Parameter	**+20%**	**-20%**
slab depth	**110,9%**	**82,0%**
web width	**113,2%**	**85,9%**
$a_{50\%}$	100,8%	95,6%
A_c	99,4%	100,9%
Mean cylinder strength	**110,1%**	**87,3%**
aggregate	100,0%	100,4%
Connection reinfo	Not present	Not present
distance reinfo	x	x
A_p	**106,7%**	**92,4%**
Diameter	x	x
type of prestress	x	x
axis distance	101,2%	**93,4%**
working prestress	100,0%	100,0%
support length	103,6%	96,2%

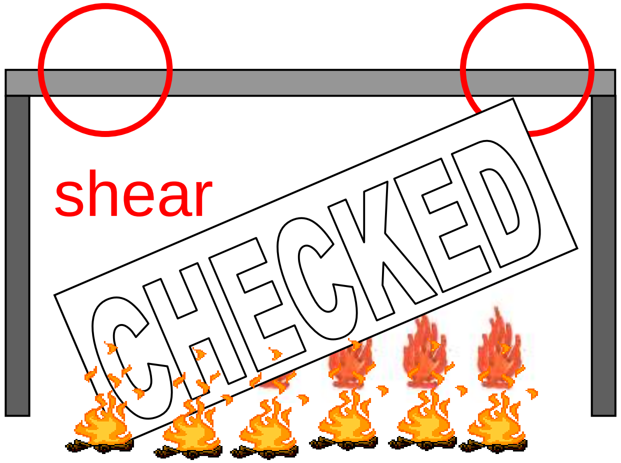
Connection reinforcement is added

Connection reinfo	149,0%	136,5%
distance reinfo	143,0%	143,0%

Conclusion of study

Recalculation of 42 fire tests according to Annex G of EN1168+A3 confirmed the validity of the formula.

With the European standard EN1168+A3 hollow core floors are safely designed for shear under fire.



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Holcofire test series ‘G’

Objective:

Analyse and confirm shear capacity through aggregate interlock, by:

1 ➔ Reinforcing bars in filled cores

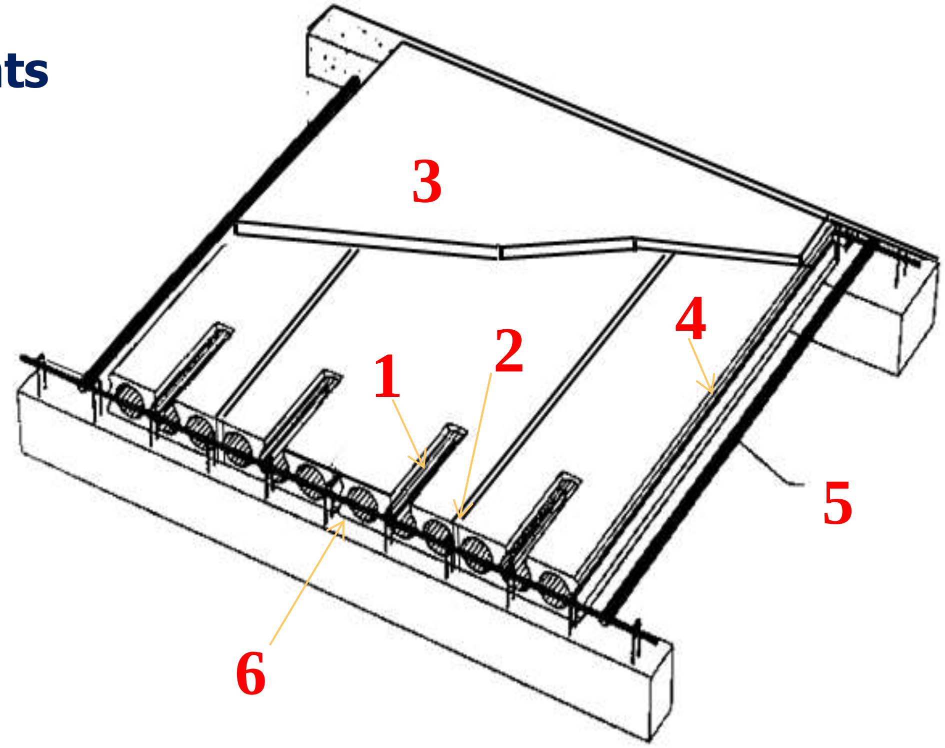
2 ➔ Reinforcing bars in longitudinal joints

3 ➔ Reinforced structural topping

4 ➔ Peripheral tie beam

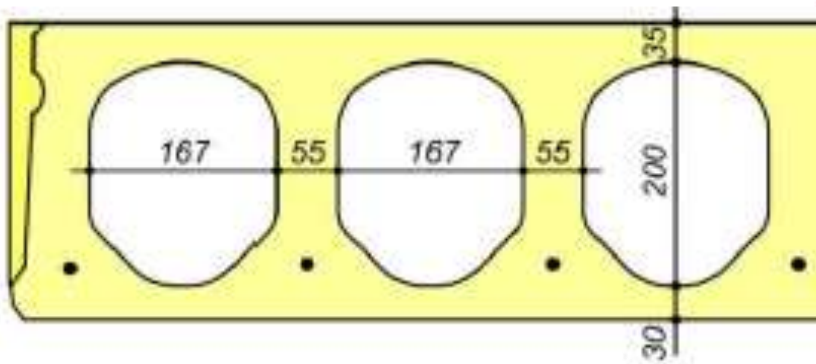
5 ➔ Restraining through longitudinal bars at test floor edges

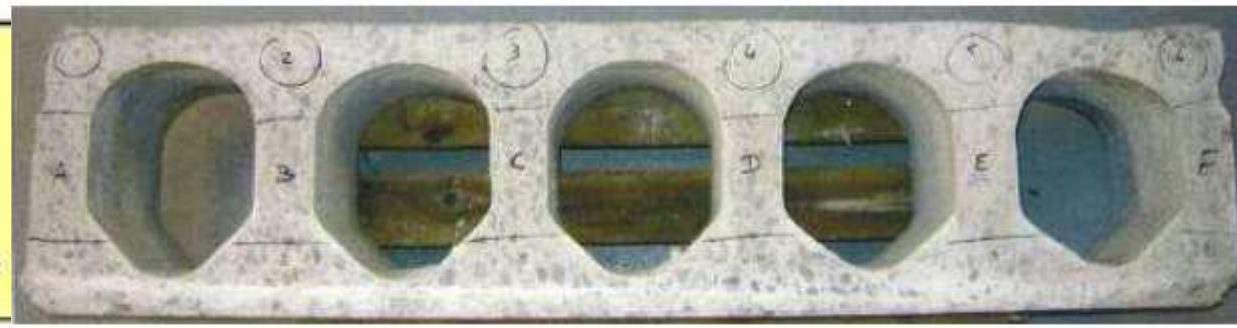
6 ➔ Projecting strands



Holcofire test series 'G' – General information

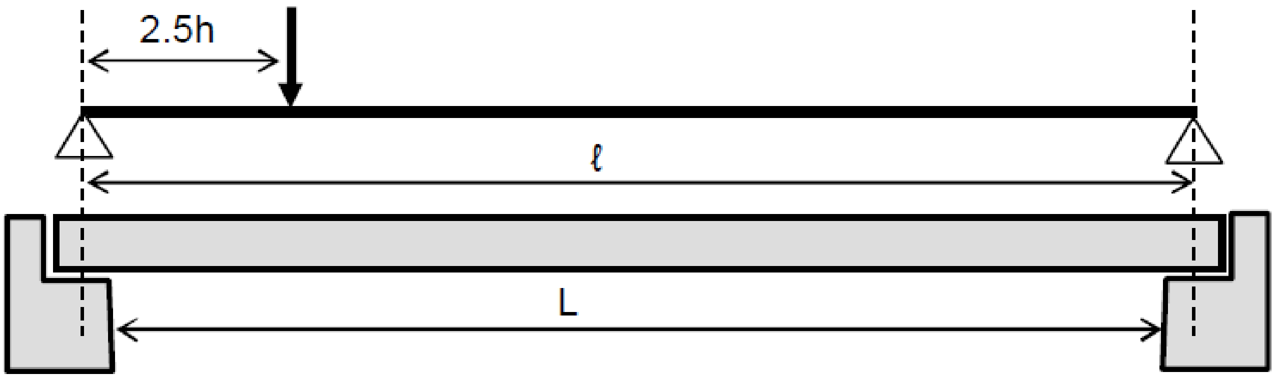
For all test in G series a 265 mm depth slab was used





- ➔ **Concrete grade C45/55- siliceous aggregate**
- ➔ **6 strands ϕ12.5 at 50 mm distance**
- ➔ **Test floor assembled one month before the test**
- ➔ **Stored indoor under 20°C – 50% RH in the climate room**
- ➔ **Topping, joints and peripheral beam: concrete grade C25/30**
- ➔ **Reinforcement B500 in peripheral beam: 2 ϕ12 + stirrups ϕ6 st=200 mm**
- ➔ **Lateral bars B500 : 1 ϕ25 on each side**

Ambiant shear tests according to EN 1168 – Annexe J



Slab #	Test date	Age [days]	Direct test load F [kN/slab]	Shear capacity $V_{R,exp}$ [kN/slab]
#31 – left	15.11.2010	89	351.3	301,7
#34 - right	17.11.2010	91	333.7	287.0
#32 – left	05.09.2011	383	337.7	291.1
#32 - right	05.09.2011	383	319.7	275.6
#33 – left	06.09.2011	384	270.2	232.9
#33 - right	07.09.2011	385	270.0	232.8
			Average per slab	262.0 kN/slab
			Average per m1	218.3 kN/m

Ultimate design shear capacity (design values: f_{ctd}, l_{pt2}) = 126.4 kN/slab

Test G1: Spalling behaviour HC

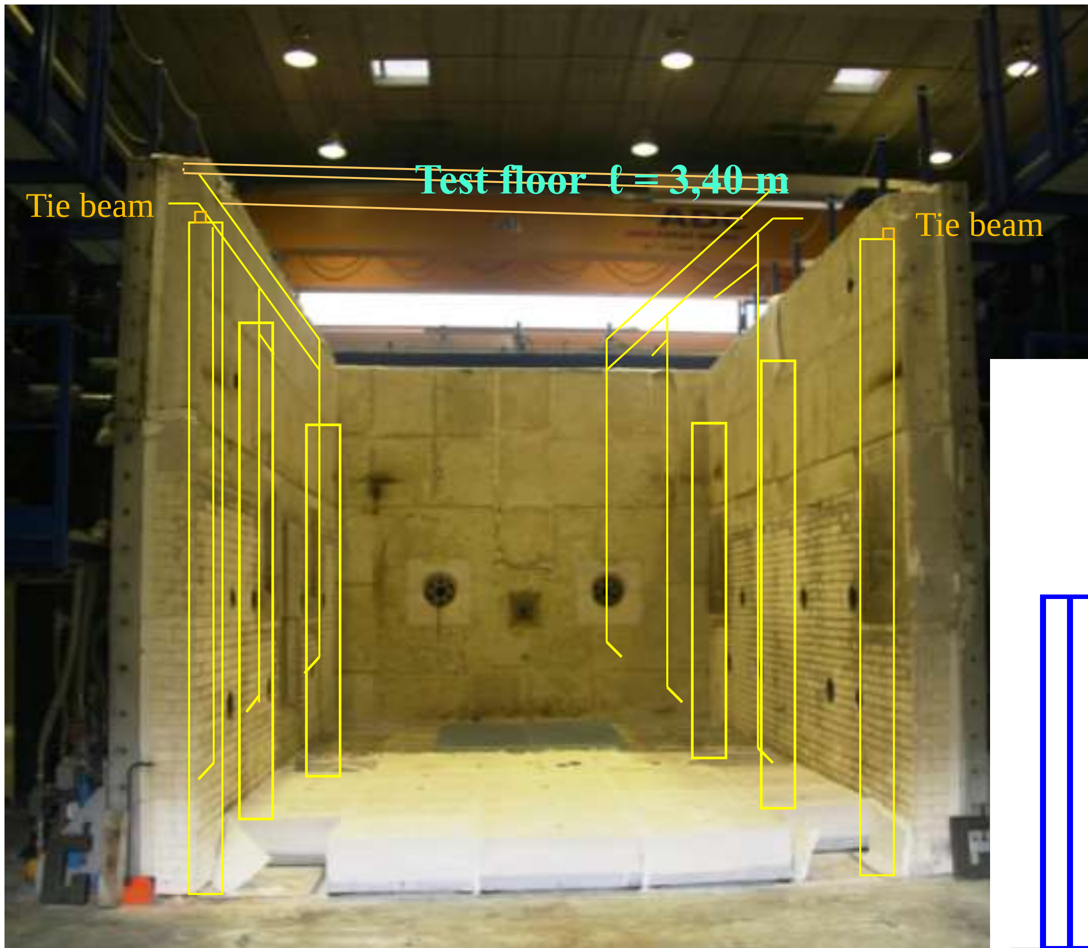
- Preliminary test in small furnace

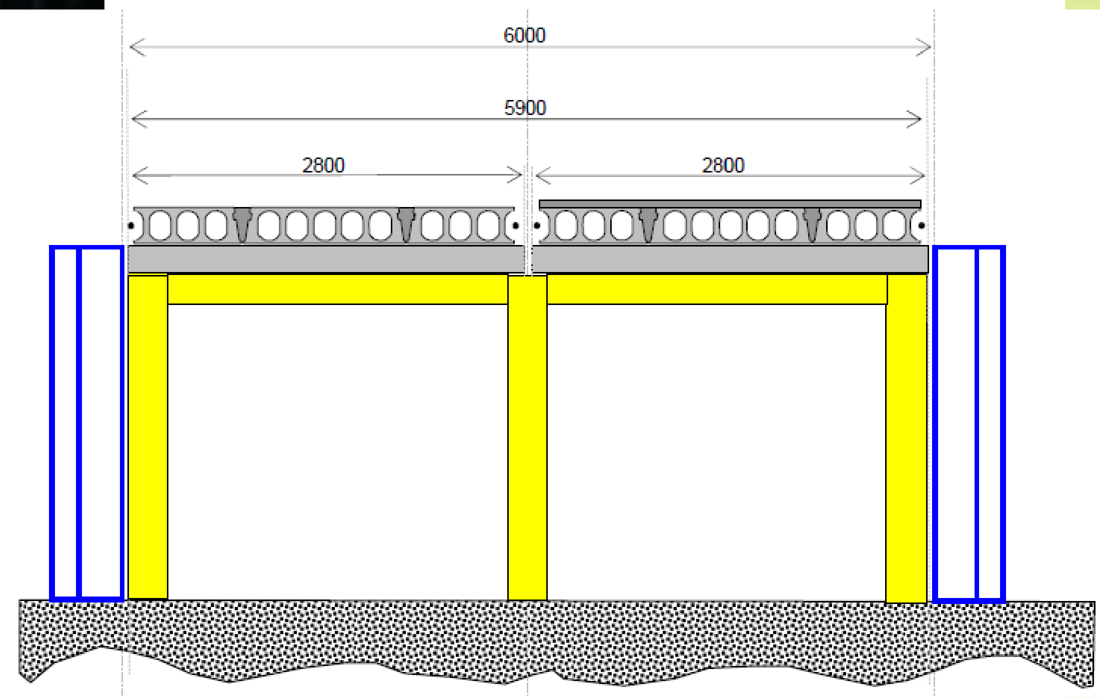
On 15.11.2010 a fire spalling test was carried out in the small furnace of CERIB, France. In this furnace, a hollow core slab is placed upside-down on the bottom of the furnace without any particular boundary condition. The slab is heated from the top. The test concluded that after 2 hours of ISO fire, no spalling was observed under unrestrained and unloaded conditions. One day after the test, vertical cracks were observed in the core at the soffit of the slab. This can easily be explained by the differential expansion of the top and bottom sections in the transversal direction.

Test series ‘G’

Test furnace at CERIB Promethee laboratory

Positioning test floor in furnace



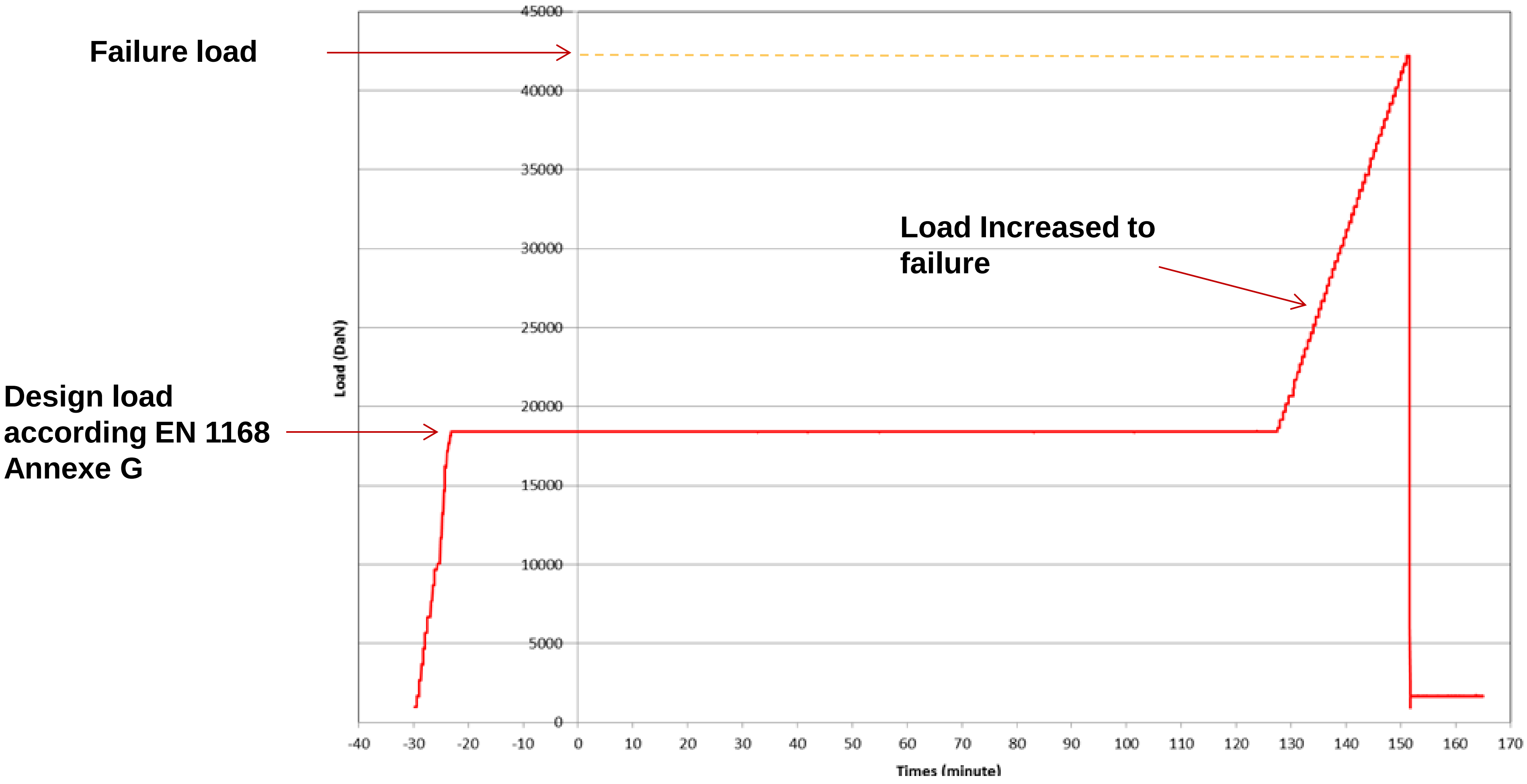


Internal view furnace and position of test floor

Test equipment

Finished test floor G5 with complete measuring equipment

Principle for loading

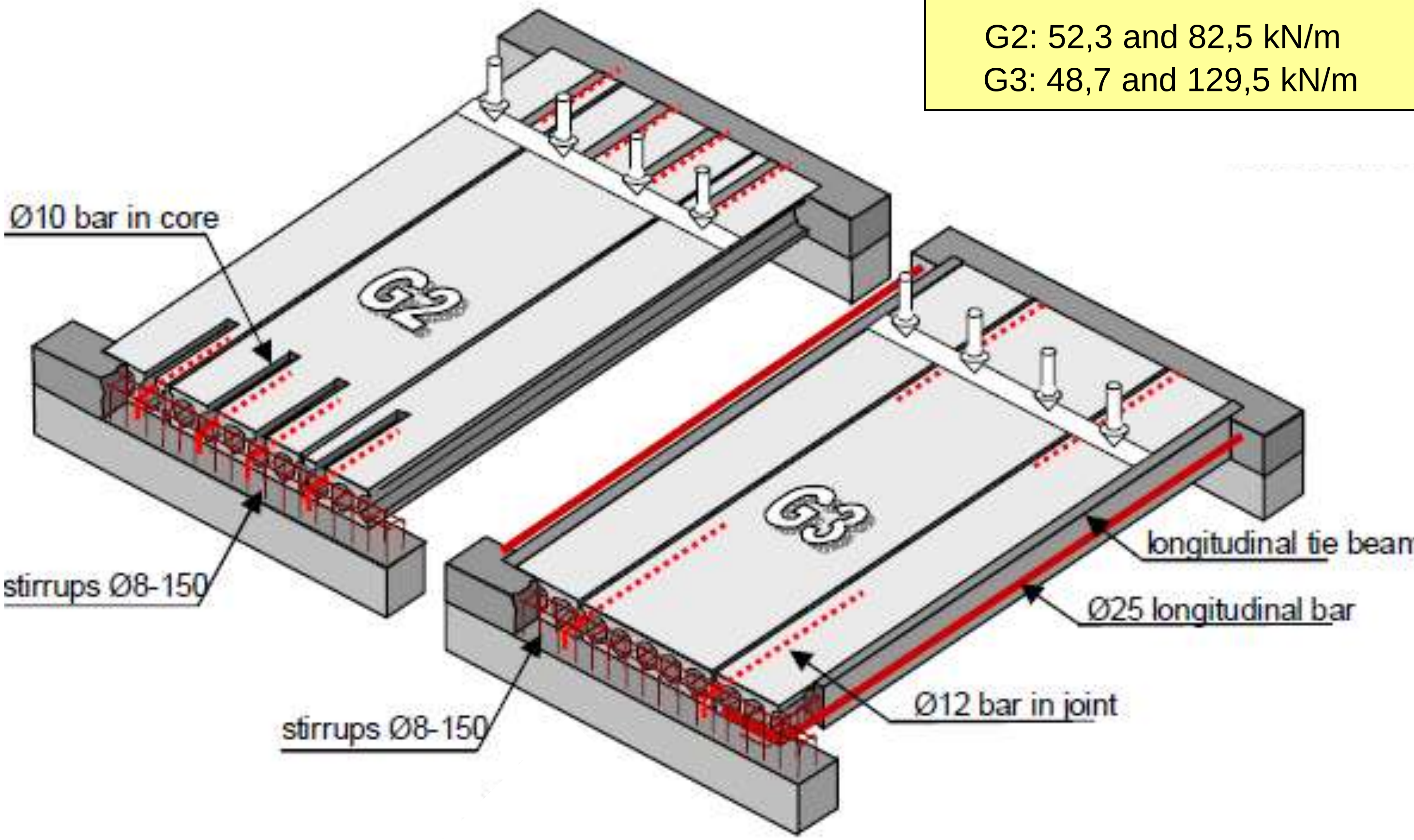


Vertical loading on the floor during test G4

Tests G2 and G3

Load at test and at failure:

G2: 52,3 and 82,5 kN/m
G3: 48,7 and 129,5 kN/m



Test parameters: bars anchored in filled sleeves and longitudinal joints, G3 being combined with peripheral beam and lateral restraining bars

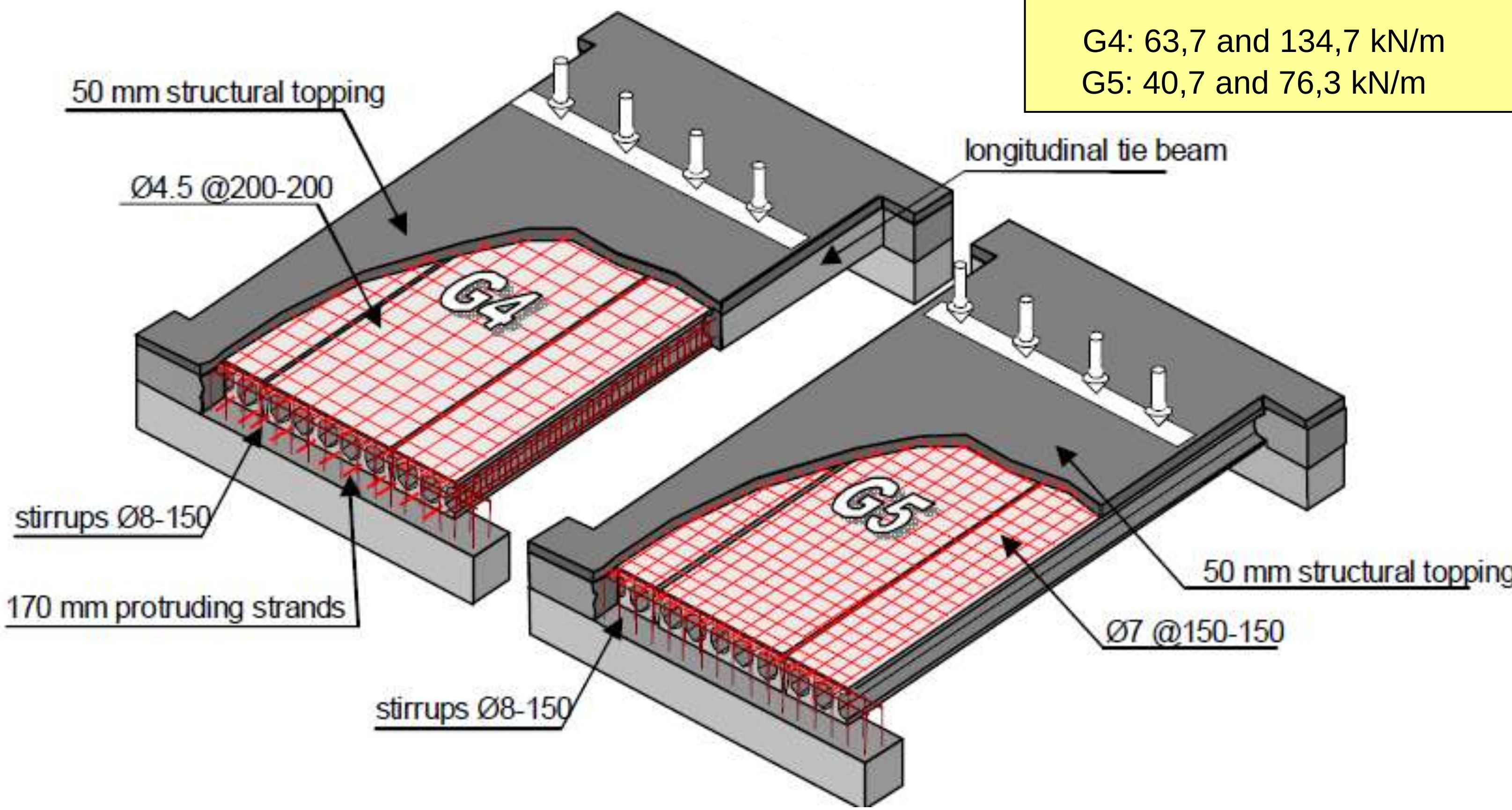
Shear crack in G2 after failure

After 120 minutes of fire, the fire was stopped and the load on floor G2 was increased until failure occurred

Tests G4 and G5

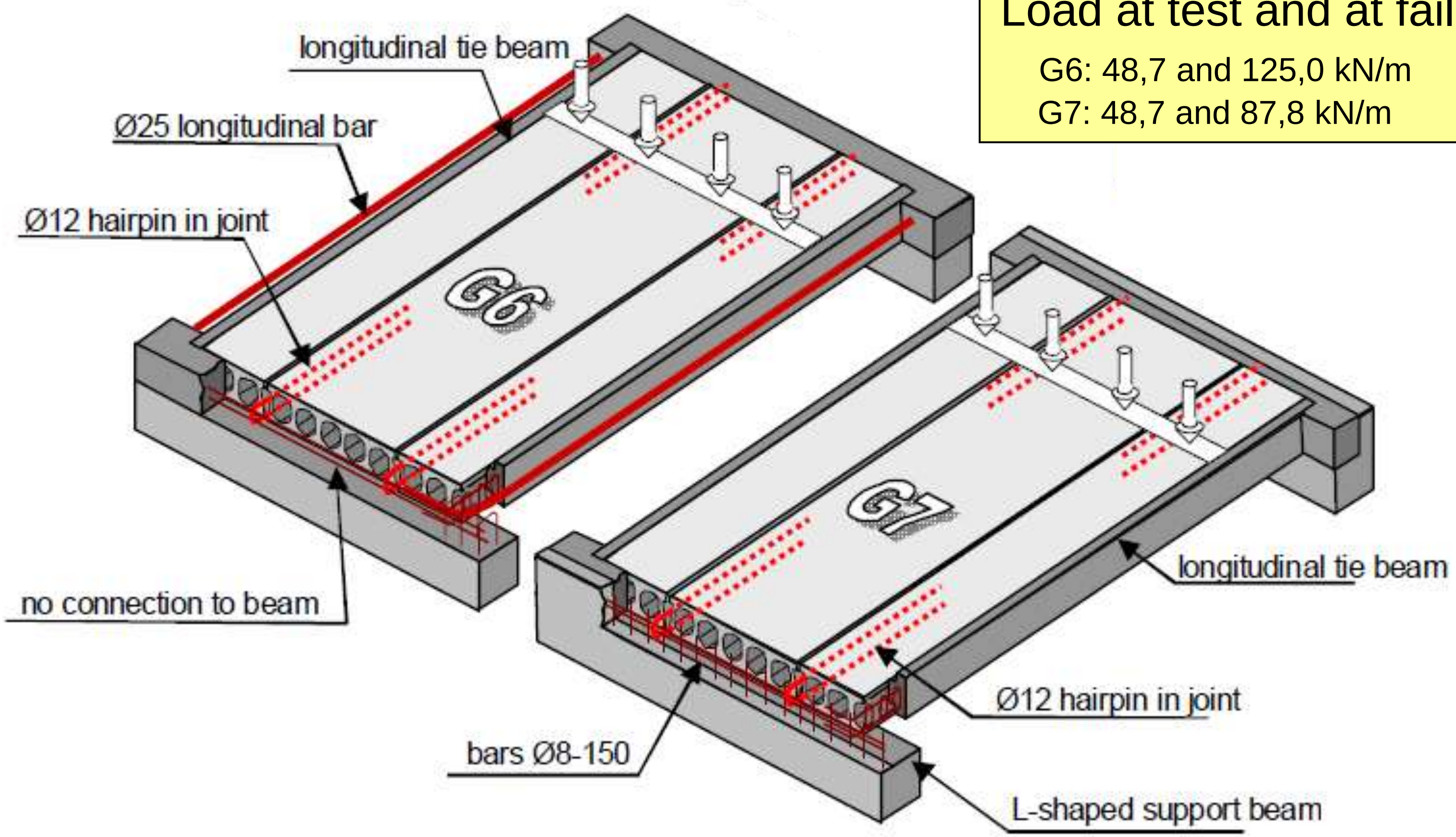
Load at test and at failure:

- G4: 63,7 and 134,7 kN/m
- G5: 40,7 and 76,3 kN/m



Test parameters: reinforced topping, peripheral beam, protruding strands

Tests G6 and G7



Load at test and at failure:

G6: 48,7 and 125,0 kN/m
G7: 48,7 and 87,8 kN/m

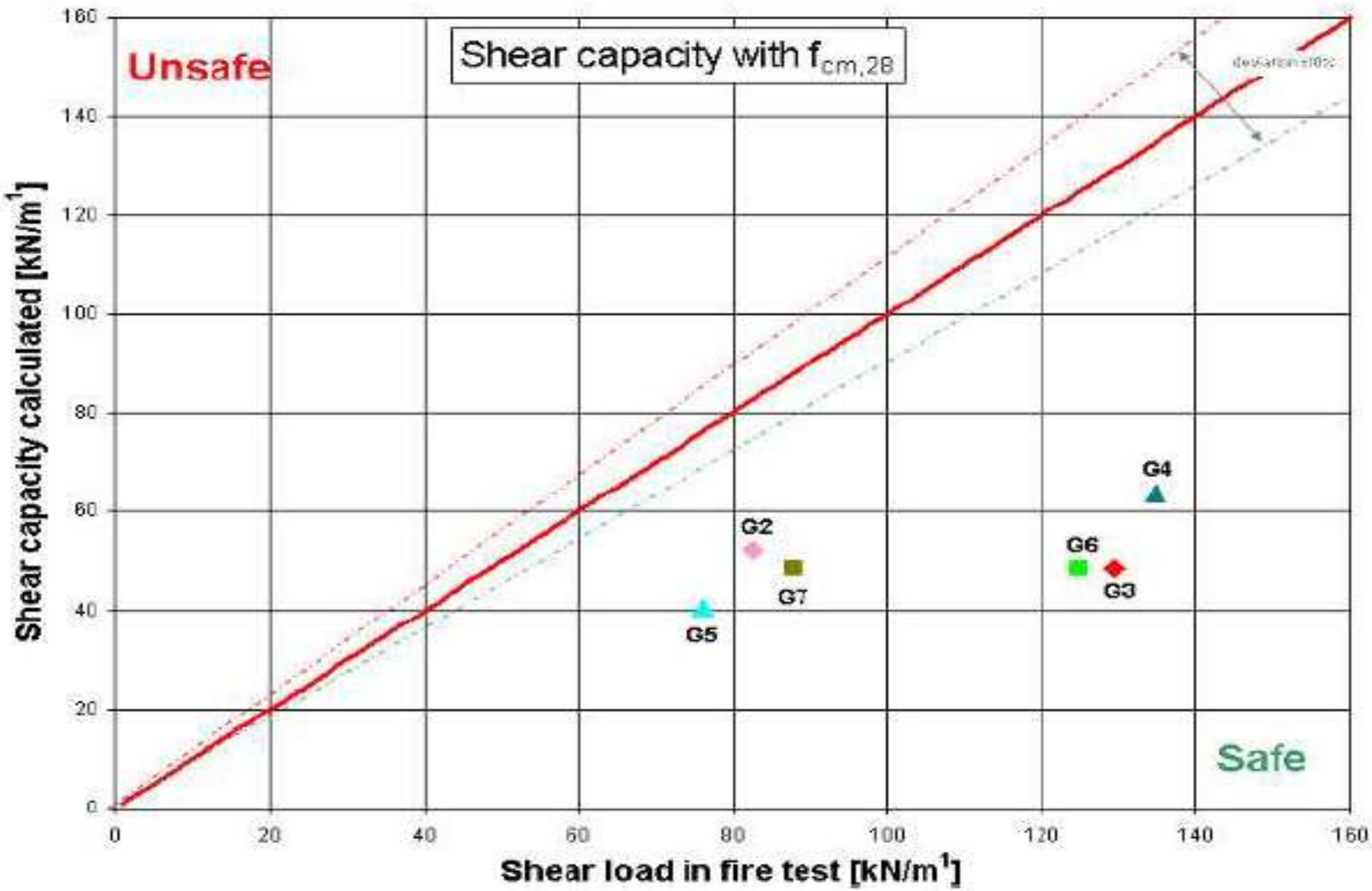
Test parameters: G6, no direct connection to support beam, combined with peripheral tie beam and lateral restraining bars; G7 connection to support beam and peripheral tie beam

Test floors G6 and G7

Test floor before casting of joints and peripheral tie beams

Summary fire tests serie G

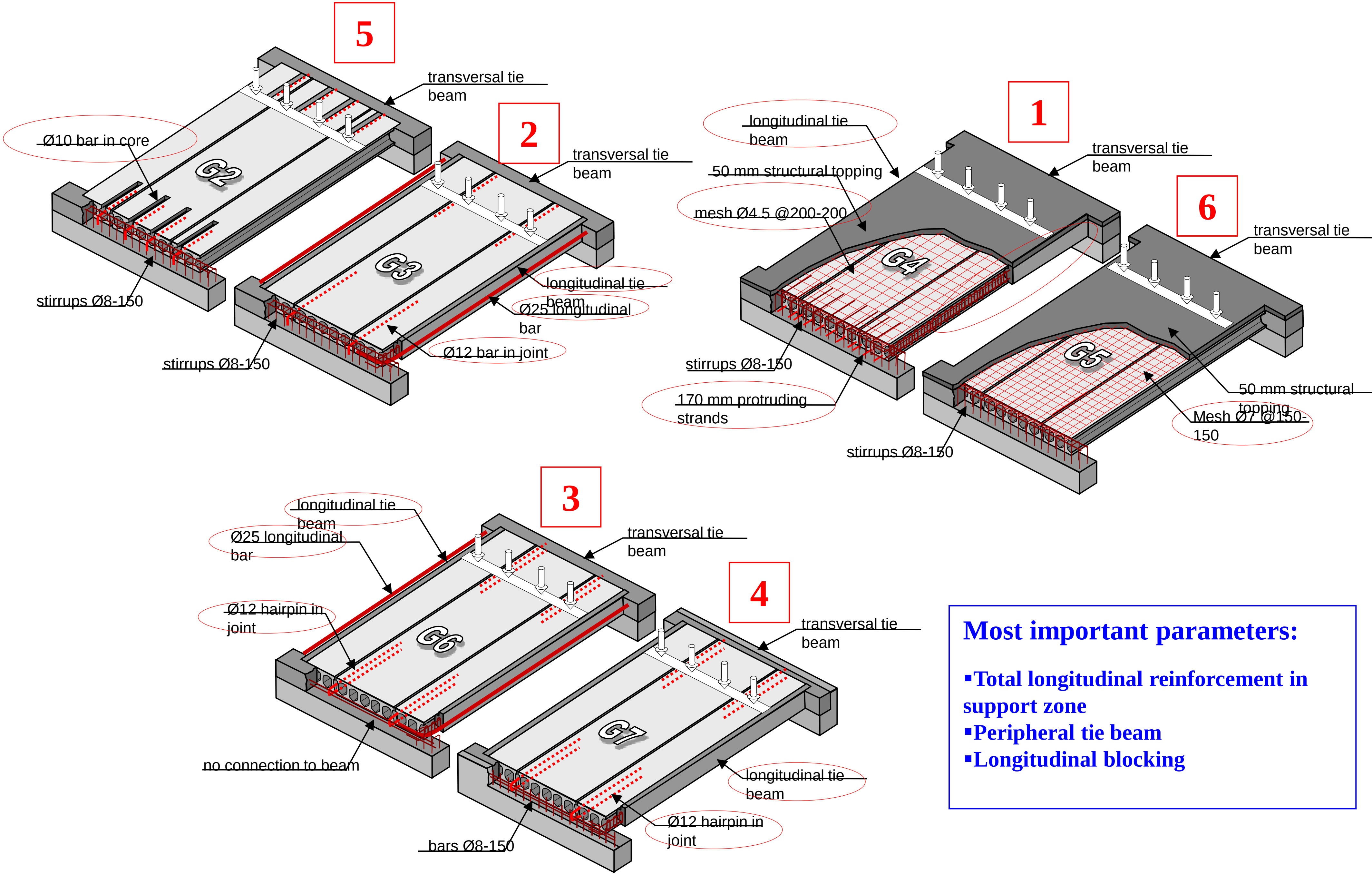
$$V_{Rd,c,fi} = \left[C_{\theta,1} + \alpha_z \cdot C_{\theta,2}\right] \cdot b_w \cdot d$$



Analysis test parameters

Parameters/Test	G2	G3	G4	G5	G6	G7
Slab thickness	265	265	265	265	265	265
Support reinforcement ▪ Vertical hairpins	yes	yes	yes	yes	no	Indirect
▪ Transversal tie bars	yes	yes	yes	yes	yes	Indirect
▪ Longitudinal bars - in filled cores	4ϕ10					
- in longitud. joints		2ϕ12			4ϕ12	4ϕ12
- in topping			ϕ 4,5 200x200	ϕ 7 150x150		
Peripheral tie beam		yes	yes		yes	yes
Structural topping			50 mm	50 mm		
Lateral bars		2 ϕ 25			2 ϕ 25	
Shear loading test (kN)	52,3	48,7	63,7	40,7	48,7	48,7
Shear failure test (kN)	82,5	129,5	134,7	76,3	125,0	87,8
Classification	**5**	**2**	**1**	**6**	**3**	**4**

Analysis test results



Most important parameters:

- **Total longitudinal reinforcement in support zone**
- **Peripheral tie beam**
- **Longitudinal blocking**

Analysis test results

Test number	Shear capacity [kN/m]	Classification shear capacity	Total longitudinal reinforcement, converted to kN,	Classification longitudinal reinforcement
G3	129.5	2	996	2
G4	134.7	1	784	3
G6	125.0	3	1027	1
G2	82.5	5	402	6
G5	76.3	6	473	5
G7	87.8	4	596	4

The large differences between the test results and the calculated values can be explained by the differences in boundary conditions (filled cores, peripheral beam, etc. It appears that the amount of reinforcement at the support plays the most important role (lateral bars, protruding strands).

Analysis test results

Test id	Test date	Experimental Shear cap. V_support [kN/m 1]	EN1168 Annex G calculated Shear cap. V_support [kN/m 1]	Experiment / calculated Shear capacity V_support [%]	capacity not calculated by Annex G (correction) V_support [kN/m 1]	Corrected calculated shear capacity V_support [kN/m 1]	Corrected Experiment / calculated Shear capacity V_support [%]
G2	23 June 2011	82,5	52,3	158%	30,0	82,3	100%
G3	23 June 2011	129,5	48,7	266%	78,6	127,3	102%
G4	22 Sept 2011	134,7	63,7	211%	70,6	134,3	100%
G5	22 Sept 2011	76,3	40,7	187%	36,0	76,7	99%
G6	21 Oct 2011	125,0	48,7	257%	78,6	127,3	98%
G7	21 Oct 2011	87,8	48,7	180%	34,6	83,3	105%

The calculated values are valid for a single HC unit with connecting reinforcement at the support. They do not take into account the additional shear capacity by the peripheral tie beam, filled cores and influences of longitudinal restraint

Overview of presentation

1. Introduction
2. EN1168 Annex G
3. Validation on 42 fire tests
4. Holcofire G tests
5. Conclusion

Conclusions from tests 'G'

- Shear capacities at fire tests are much higher than calculated with Annex G
- Longitudinal connections at the support zone are playing an important role in the shear capacity at fire because they are keeping the vertical thermal cracks closed and restore the shear capacity of the slabs through aggregate interlock
  - Reinforcement bars in joints or filled cores
  - Reinforced peripheral tie beam
  - Protruding strands
  - Lateral external longitudinal bars Ø25 (simulating blocking of thermal expansion)
- Vertical connections with the supporting beam through hair pins are not strictly needed, but recommended
- Structural toppings have a moderate positive influence on the shear capacity
- The postulated failure mode looks to be correct
- The calculation formula has a high reliability
- Prestressed HC floors have a high shear capacity