Behavior and Design of Concrete Structures Under Natural Fires

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ASCE/SEI Manual of Practice No. 138:
Performance-Based Fire Design Guidance for Concrete Structures

Monday, March 28, 2022
Orlando, Florida

ACIF project supported by ACI 216 for fire design

Context

- CRC 2020 P0039 Project funded by the ACI Foundation with support of ACI 216 Committee
- Advisory panel: A. Masek & T. Ladely (ACIF), F. Robert (CERIB), K. Mueller (ACI 216)
- Broader effort to develop performance-based structural fire design incl. ASCE 7 and MoP 138

Objectives

- Understand and assess the possibility of failure during the cooling phase
- Establish an analysis procedure to evaluate resistance to full burnout under real fires
- Propose simple design provisions complementary to the standard fire resistance rating

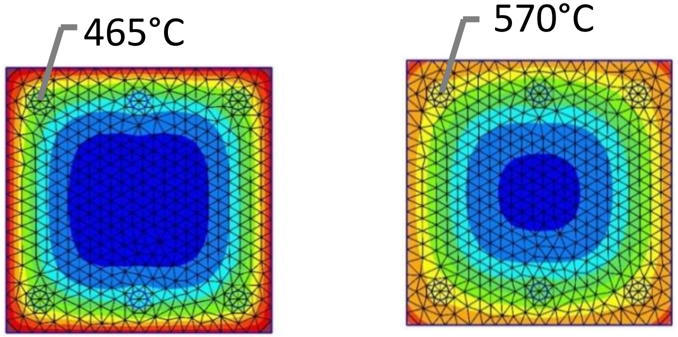
Why assessing the response during the cooling phase?

This is a new need arising from the emergence of SFE

- Structural Fire Engineering (SFE): explicitly assessing the response to fire
- Real fires include *heating* and *cooling*
- SFE considers *performance objectives*: e.g., design to resist to full fire burnout, resilience

This is important because structures (all materials) may fail during cooling

Delayed temperature increase in sections



Time of max gas temperature t_{max}

t_{max} + 30 minutes

Real structural collapse

Switzerland, 2004

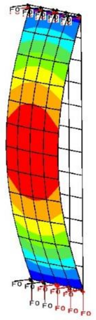
What do we need for this assessment?

Data on concrete properties during cooling phase

- Experimental data on thermal and mechanical properties
- Need for specific experimental protocols
- Provisions in standards and models for simulations

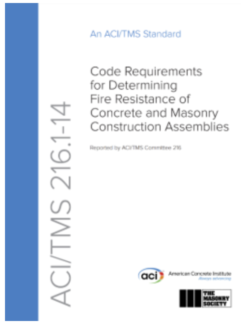
Data on concrete structural members' response during cooling phase

- Using Finite Element Method calibrated on available experiments
- Need for specific numerical protocols, including natural fire exposure
- Numerical database on burnout resistance



Simple design methods

- Provide guidance for pre-design to account for vulnerability to cooling



ACI/TMS 216.1-14

An ACI/TMS Standard

Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies

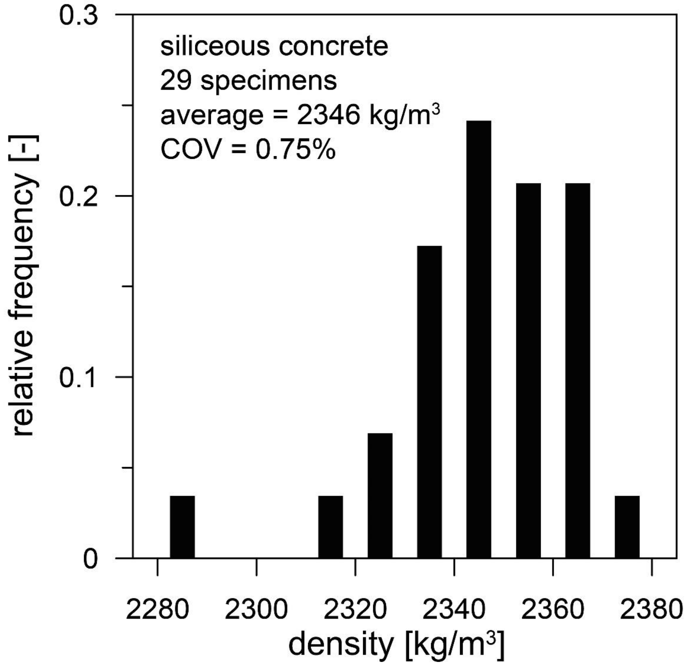
Materials properties – Experimental program

Studied 4 concrete mixes

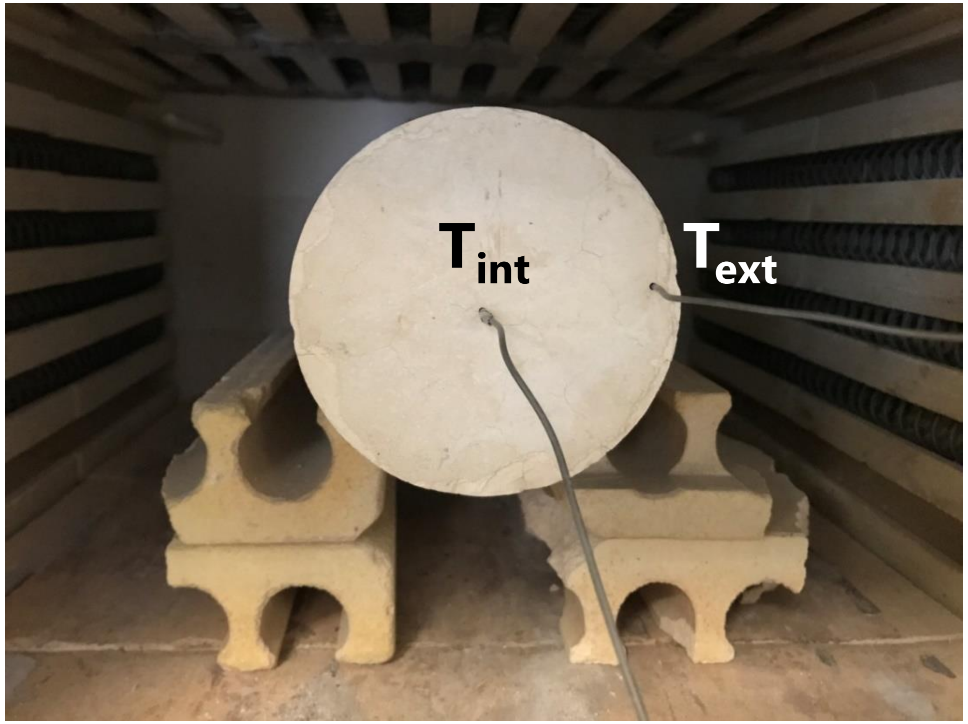
- Normal strength, siliceous and calcareous, with/without PP

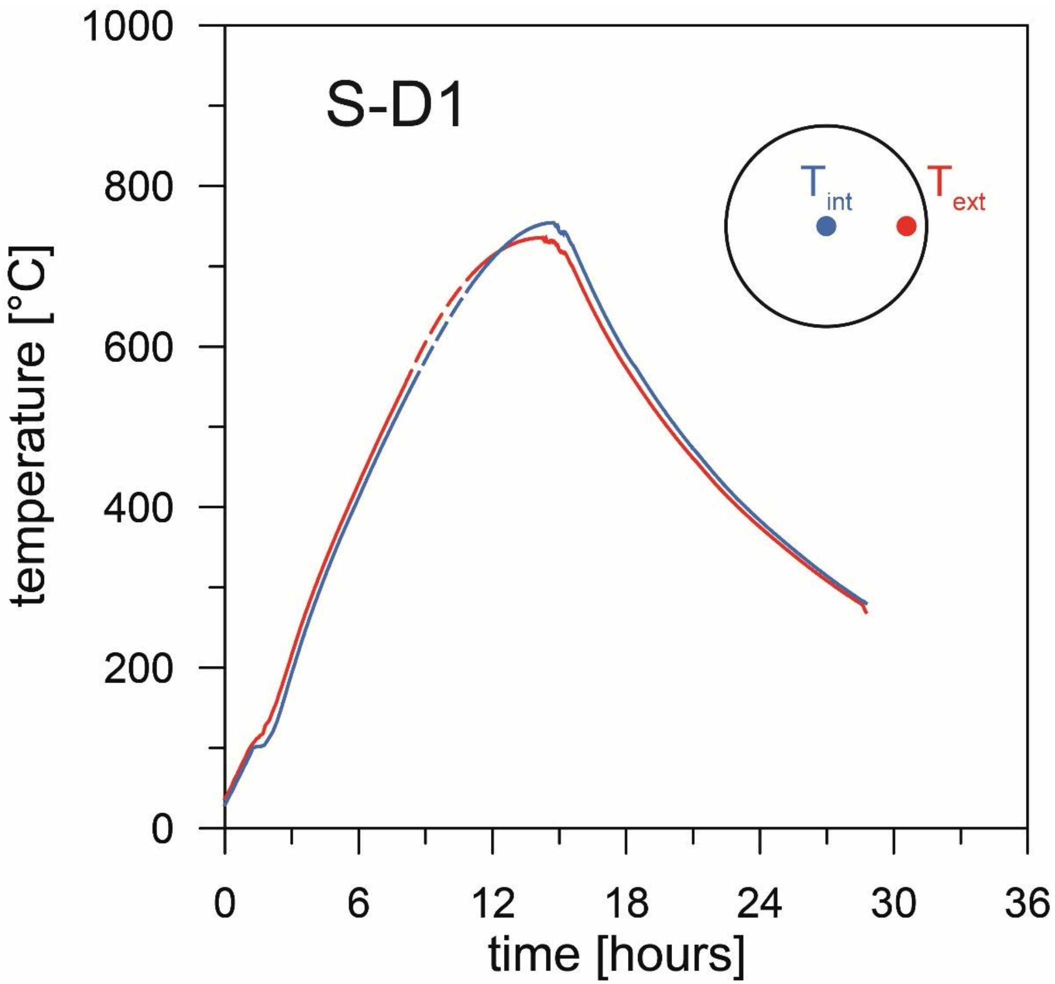
Number of specimens (for each mix)

- Thermal diffusivity: 4 specimens (∅ = 100 mm, h = 300 mm)
  - 2 thermal cycles
  - 2 specimens for repeatibility
- Compressive strength: 30 specimens (∅ = 100 mm, h = 250 mm)
  - 10 test modalities
  - 3 specimens for repeatibility



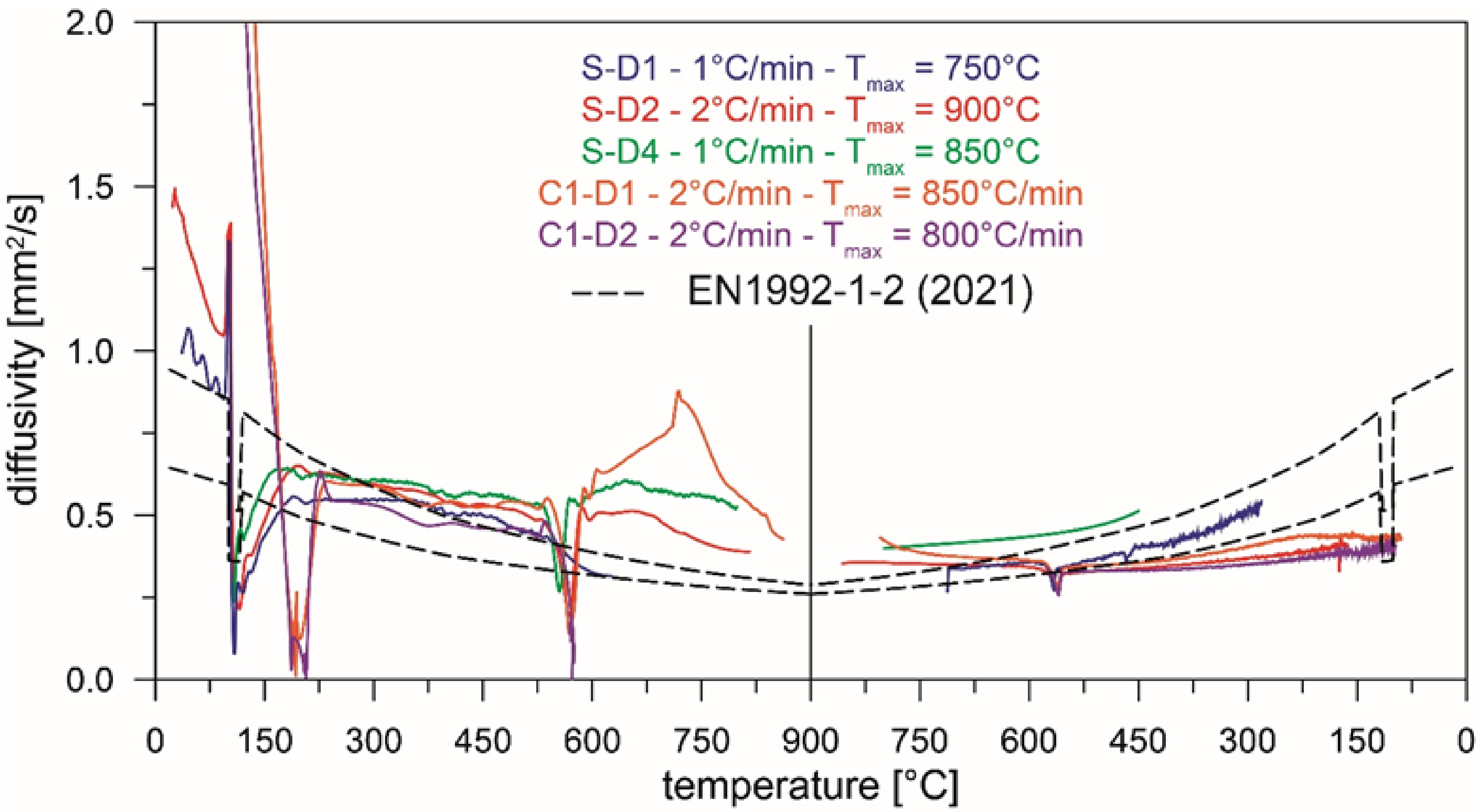
Diffusivity tests – Temperature measurements





Thermal diffusivity calculated from measurements of temperatures T_{int} and T_{ext} and heating rates

Test results – Thermal diffusivity (all specimens)



Thermal diffusivity is **irreversible in cooling** (for various maximum temperature and heating rate)

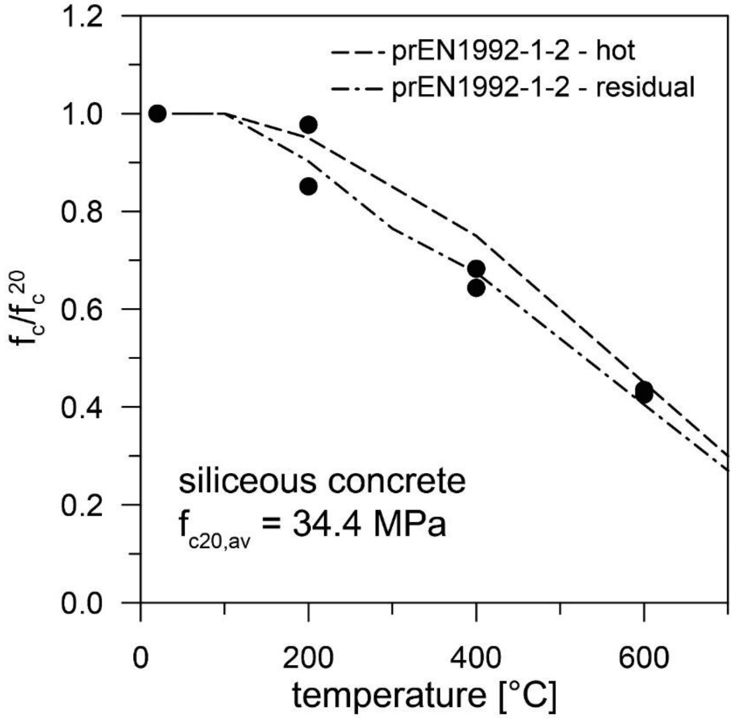
Compressive tests procedure

- Definition of two target temperatures:
  - T_{max} = maximum temperature during the thermal cycle
  - T_{test} = temperature at which the test is performed
- 10 tests per mix (repeatibility excluded)
  - T_{max} = T_{test} = 20°C (**1**)
  - T_{max} = 200°C, T_{test} = 20 and 200°C (**2**)
  - T_{max} = 400°C, T_{test} = 20, 200 and 400°C (**3**)
  - T_{max} = 600°C, T_{test} = 20, 200, 400 and 600°C (**4**)

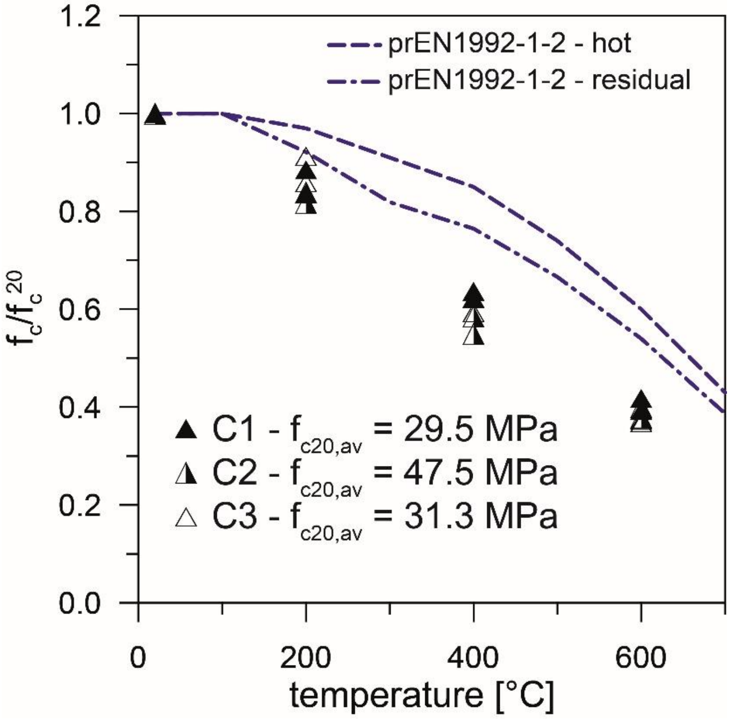
		T_{max} [°C]			
		20	200	400	600
T_{test} [°C]	20	x	x	x	x
	200		x	x	x
	400		-	x	x
	600		-	-	x

- Heating rate = 1°C/min = 30°C/h (RILEM)
- Cooling rate = same as in heating if $T_{test} \geq 200$°C, furnace-controlled if T_{test} = 20°C
- Rest time at T_{max} and T_{test} = 2 hours

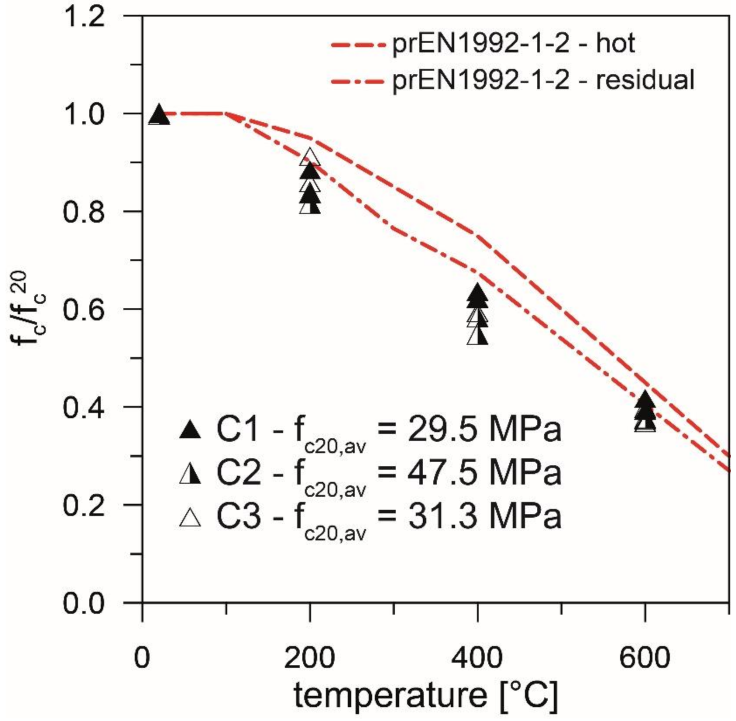
Residual tests – Compressive strength



Siliceous mix (S) vs
standard curves for **SILICEOUS** aggregate

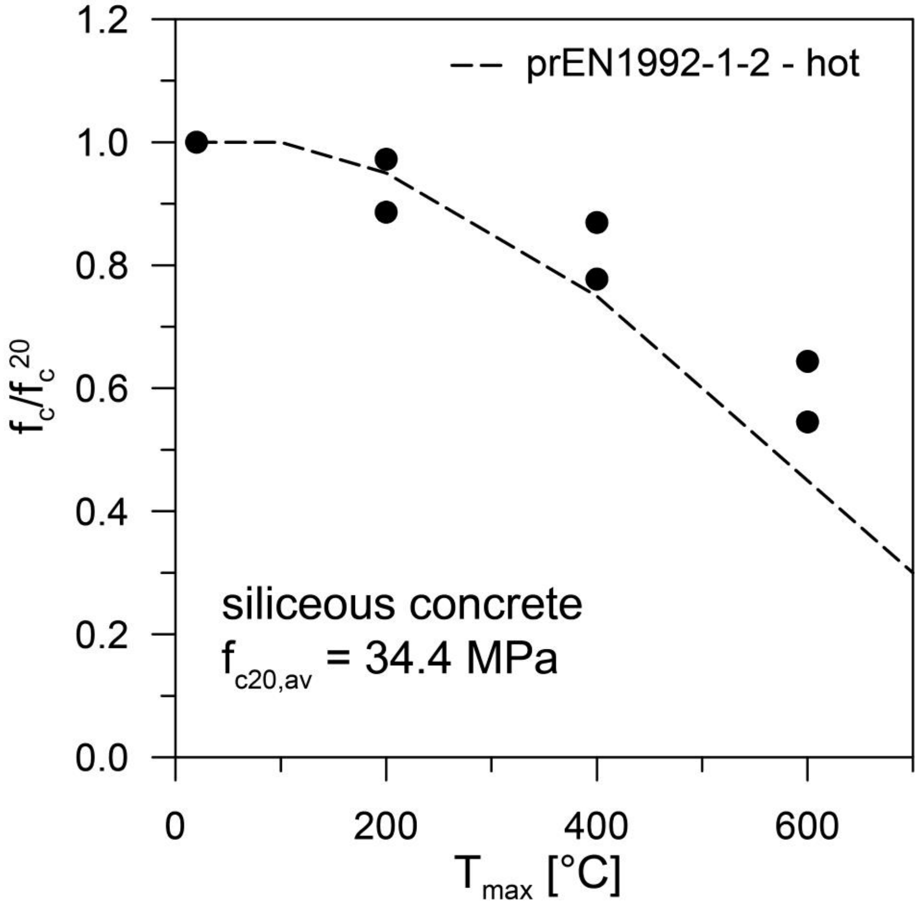


Calcareous mixes (C1-C2-C3) vs
standard curves for **CARBONATE** aggregate

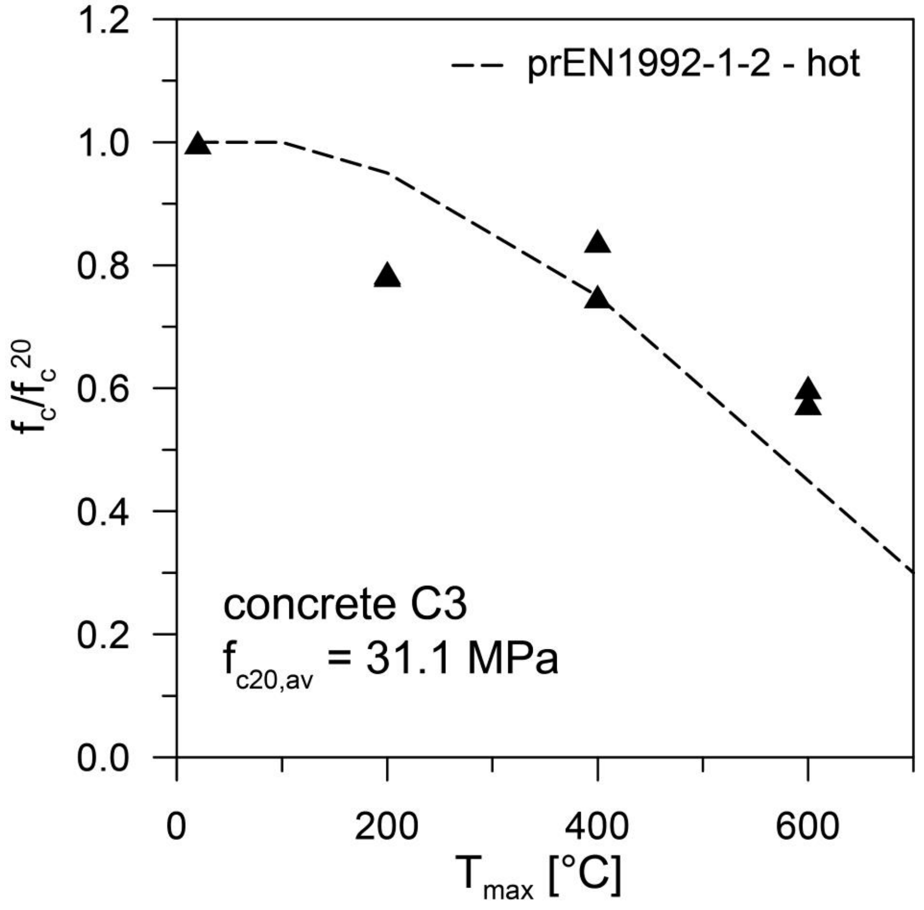


Calcareous mixes (C1-C2-C3) vs
standard curves for **SILICEOUS** aggregate

Hot tests – Compressive strength

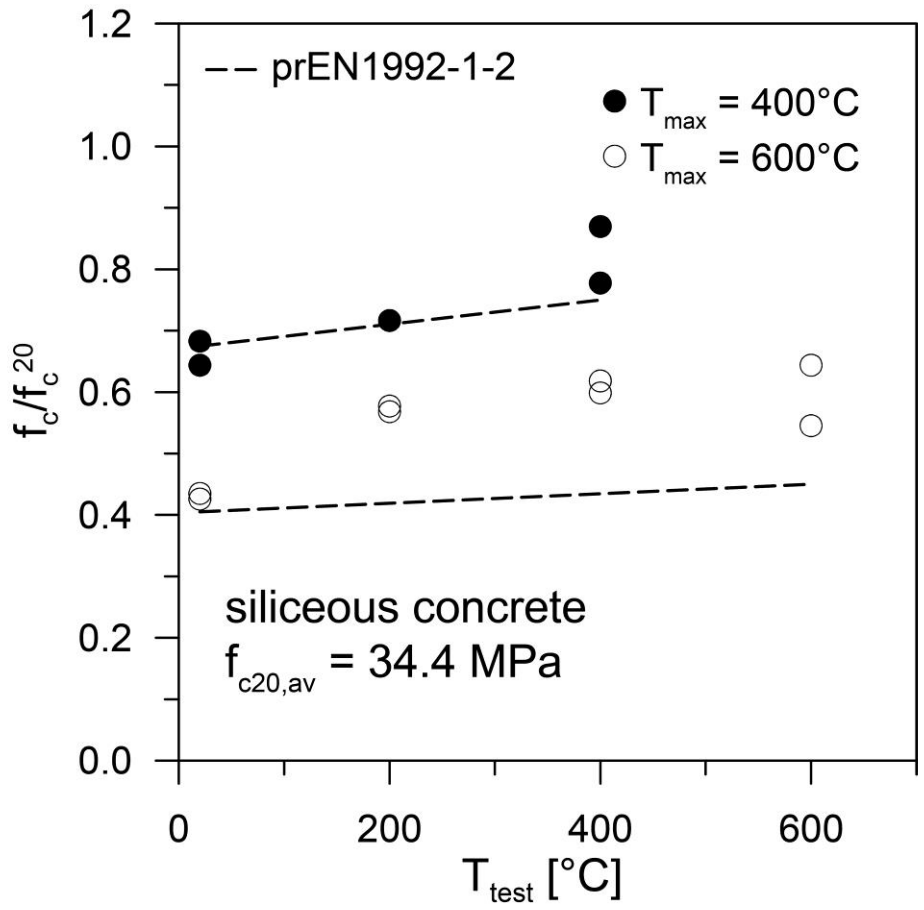


Siliceous mix (S) vs
standard curves for **SILICEOUS** aggregate

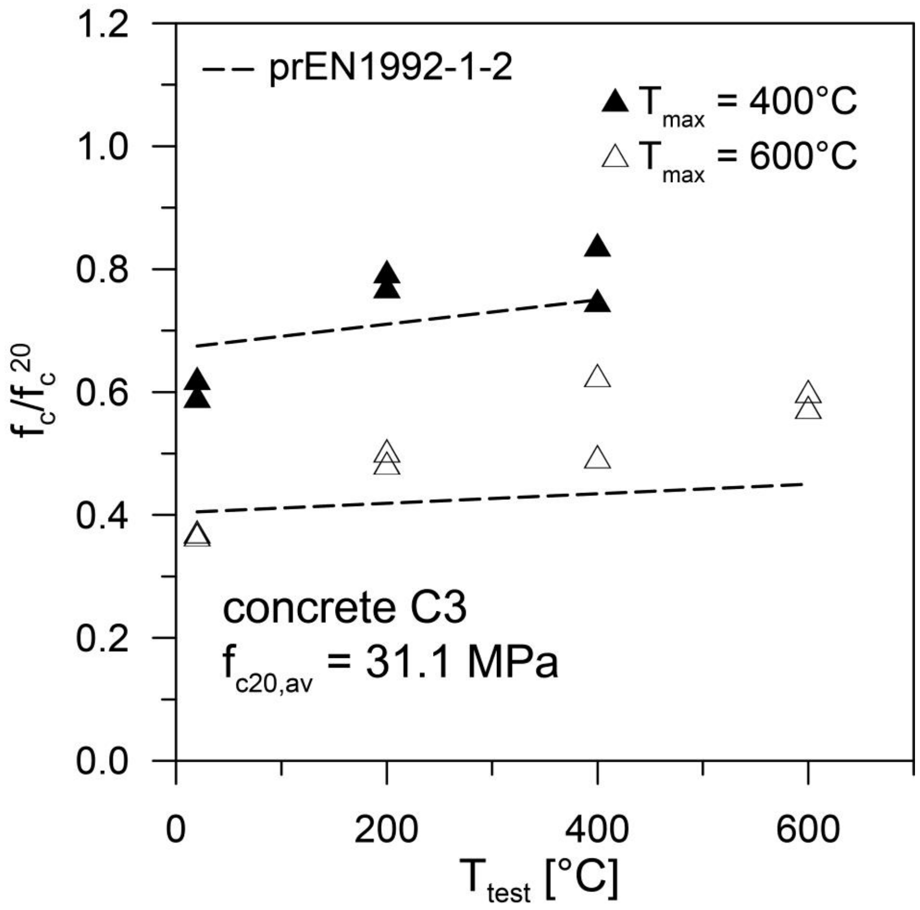


Calcareous mix (C3) vs
standard curves for **SILICEOUS** aggregate

Intermediate (cooling) tests – Compressive strength



Siliceous mix (S) vs
standard curves for **SILICEOUS** aggregate



Calcareous mix (C3) vs
standard curves for **SILICEOUS** aggregate

Main outcomes of the experimental program

Thermal diffusivity

- **In the heating phase**, agreement with the two boundary curves provided by the Eurocode standard, especially below 500 °C.

- **In the cooling phase**, **irreversibility.** Consider that, upon cooling, the diffusivity remains constant, and equal to the value attained at the maximum temperature reached during the thermal cycle.

Compressive strength

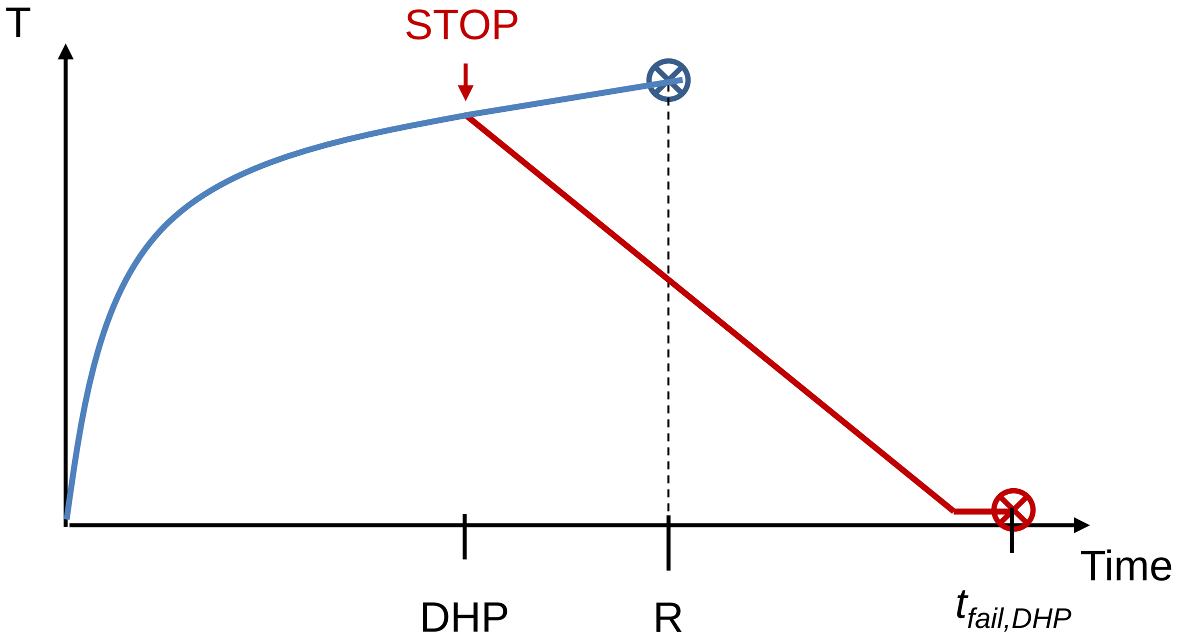
- **Residual compressive strength** measured after heating to 200, 400 and 600 °C shows a greater loss of strength than the provisions for elevated temperature: **residual < hot**. Suggestion to adopt the tentative provisions given in prEN 1992-1-2 for siliceous concrete.

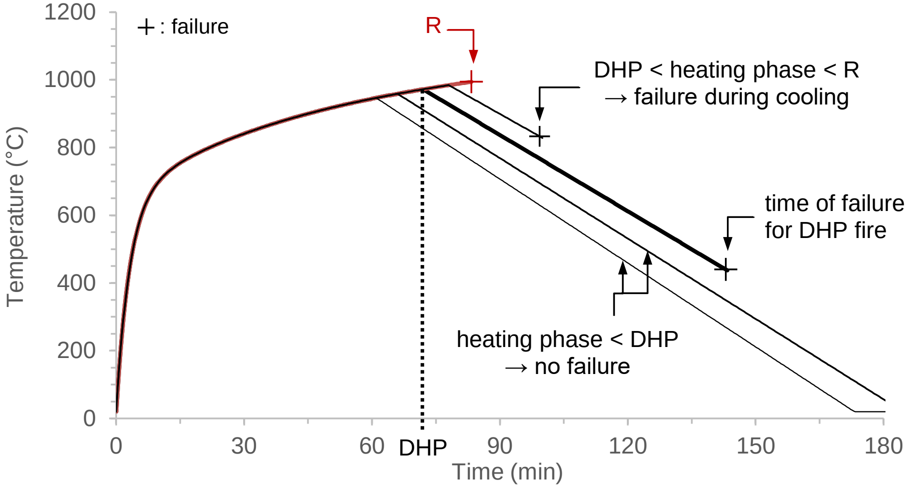
- **Hot compressive strength** at 200-600 °C in line with current provisions for elevated temperature.

- **Compressive strength in cooling** was measured using a new protocol. The data confirmed that cooling to 20°C leads to an additional reduction in strength, however, the reduction is not linear between the hot strength and the residual strength.

Numerical analysis of concrete members to determine the burnout resistance

Find DHP: shortest Duration of Heating Phase that leads to failure



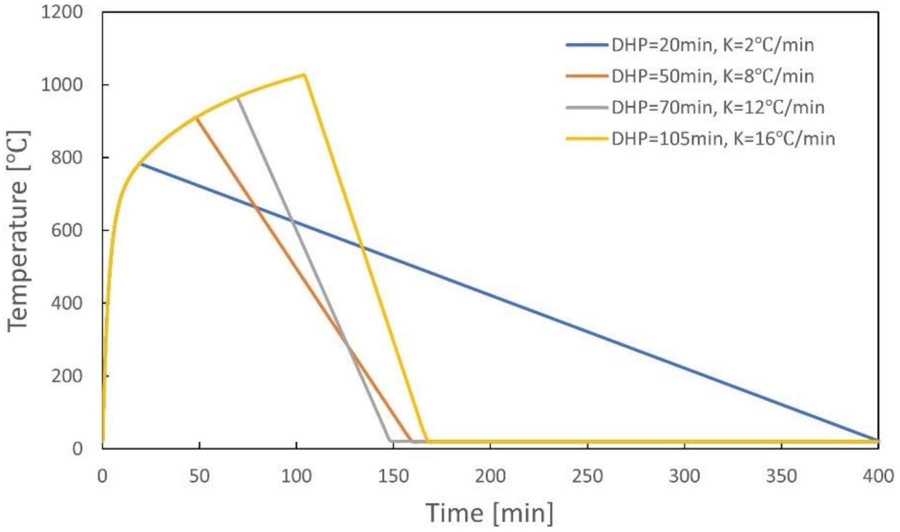


- Iterative analyses (FEM) subjecting the concrete member to varying durations of fire exposure
- ***DHP < R but time of failure > R***

Defining a “standard” natural fire exposure

- Need for a systematic method of assessment
- EN parametric fires with ISO 834 heating and linear cooling
- Zone fire simulations and Epernon tests data to calibrate cooling

For benchmarking purpose



$$\theta_g = 20 + 1325(1 - 0.324e^{-0.2t} - 0.204e^{-1.7t} - 0.472e^{-19t}) \qquad for\ t \leq DHP$$

$$\theta_g = \theta_{g,max} - K\ (t - DHP) \qquad for\ t > DHP$$

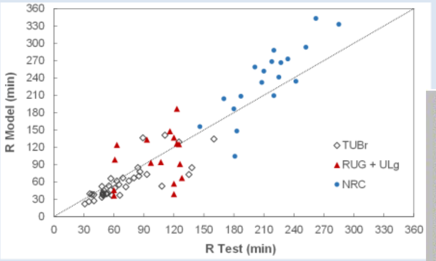
where t = time (in hr)

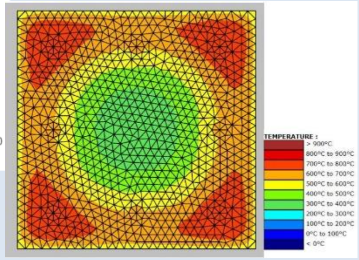
DHP = duration of heating phase (in hr)

K = cooling rate (in °C/hr), taken within 120-1200 °C/hr

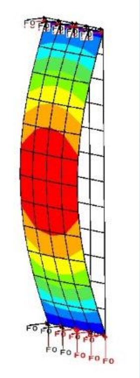
Numerical analysis of concrete members under natural fire

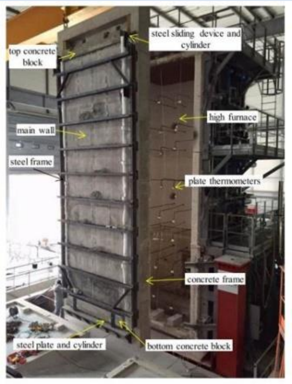
- Generate data on burnout resistance of 4 types of concrete members through FE analysis
- FEM calibrated on tests then parametric analyses under ***standard natural fires*** for ***burnout resistance***



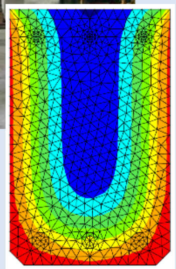


RC columns
(74 specimens, multiple labs)

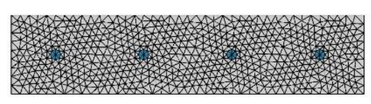




RC wall (Pham et al., 2021)



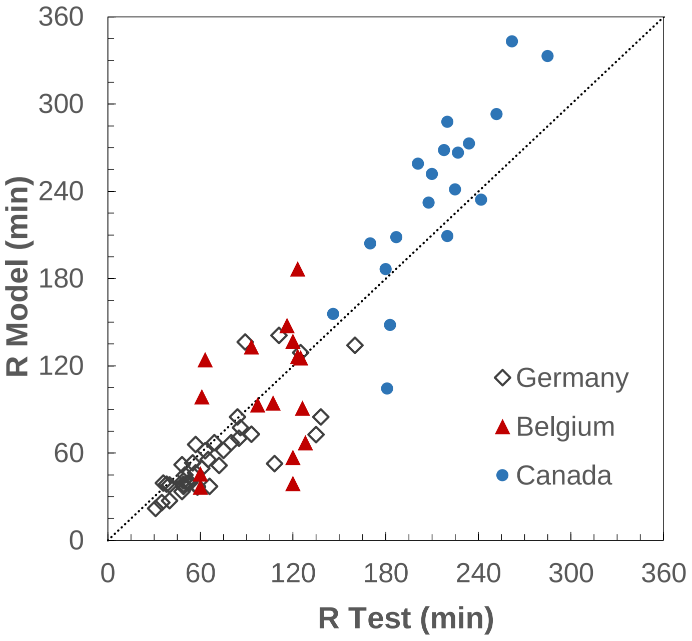
RC beam (Sauca, 2017)



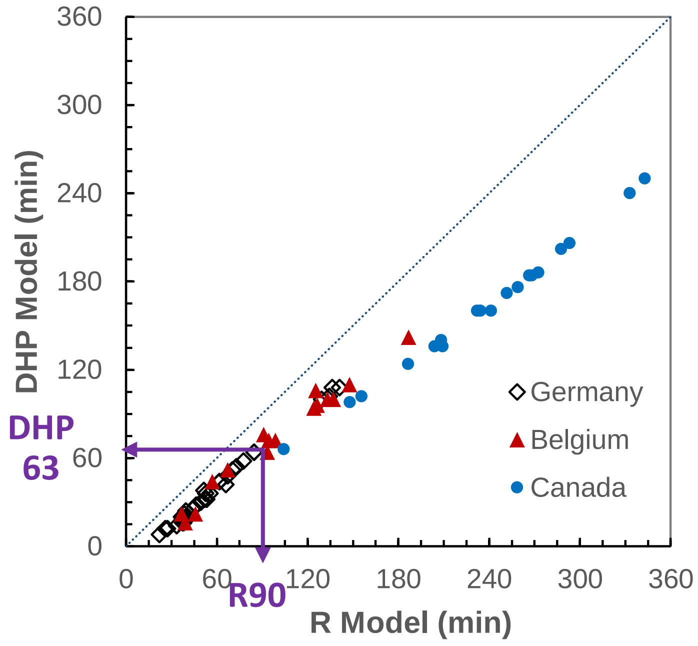
PC slabs (Maluk et al., 2015)

Reinforced concrete columns

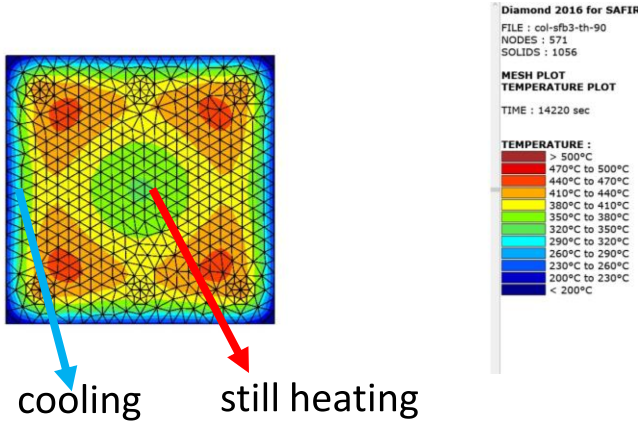
- Database: 74 fire resistance tests
- Tests modeled in SAFIR → Rmodel vs Rtest
- Then, burnout resistance DHP found with SAFIR



Average: 0.95 StDev: 0.29



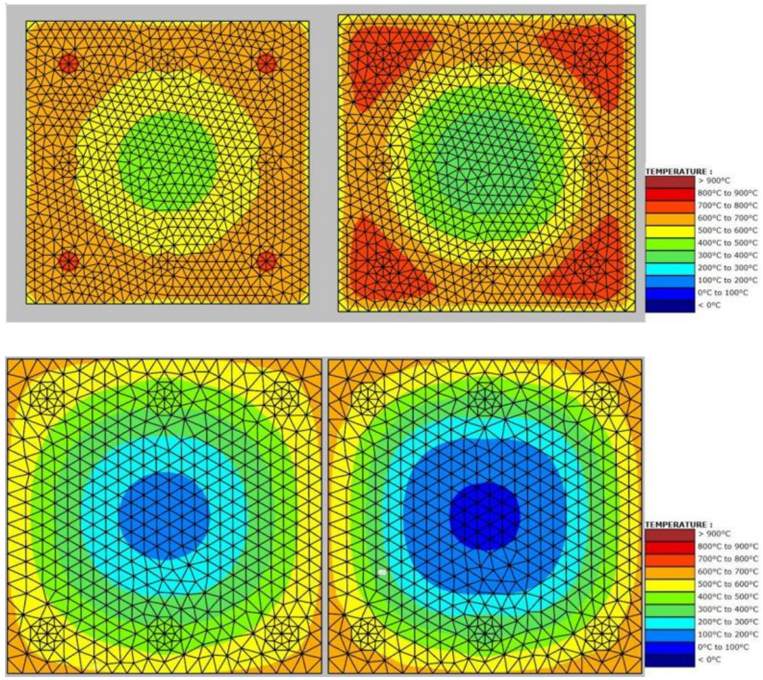
DHP ≈ 0.7 R



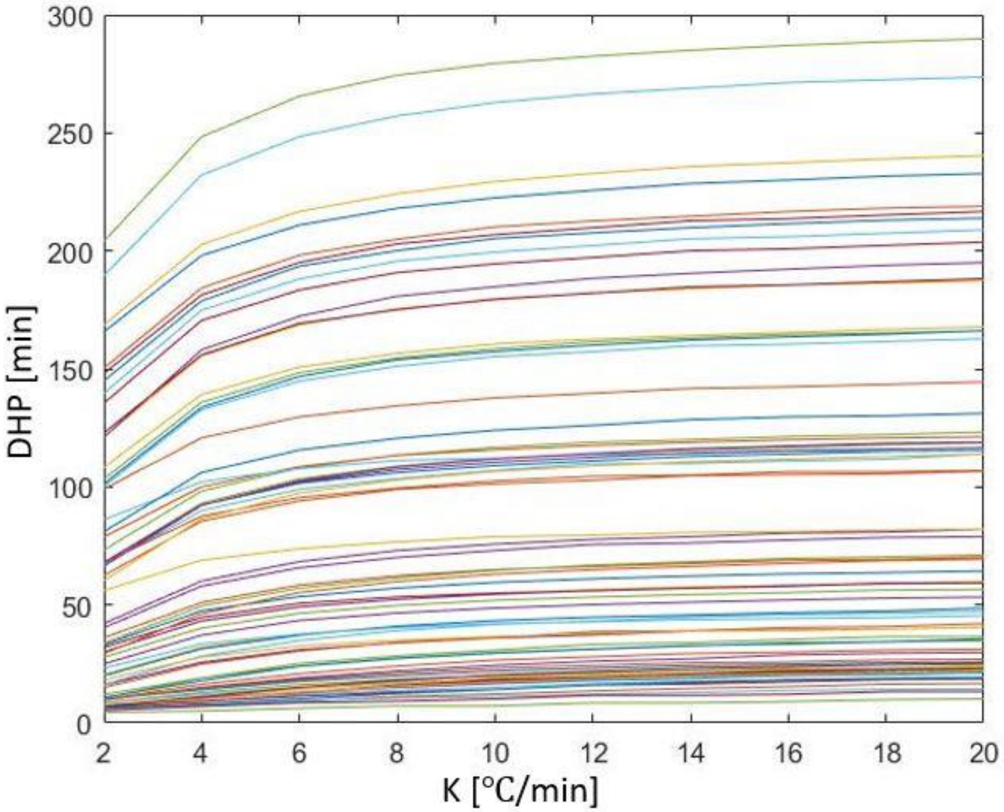
Gernay, T. (2019). Fire resistance and burnout resistance of reinforced concrete columns. *Fire safety journal*, *104*, 67-78.

Reinforced concrete columns

- The 74 columns are simulated under natural fires with 10 cooling rates *K* (~2-20 °C/min)



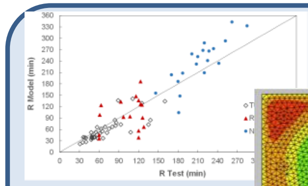
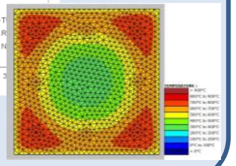
Temperature distribution at time of failure (different *K*)



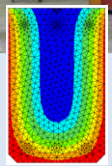
Each curve represents – for one column – the shortest duration of heating phase (following the ISO 834 curve) that leads to collapse of the column, as a function of the cooling rate in the decay phase

Slower cooling (*K* ↘) increases the risk of failure during cooling (DHP ↘) for a given R-rating

Numerical database of burnout resistance

RC columns
(74 specimens, multiple labs)

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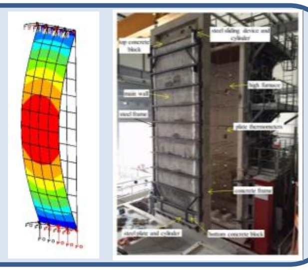

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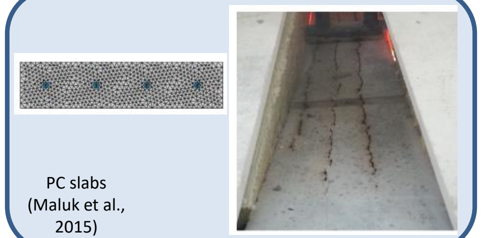
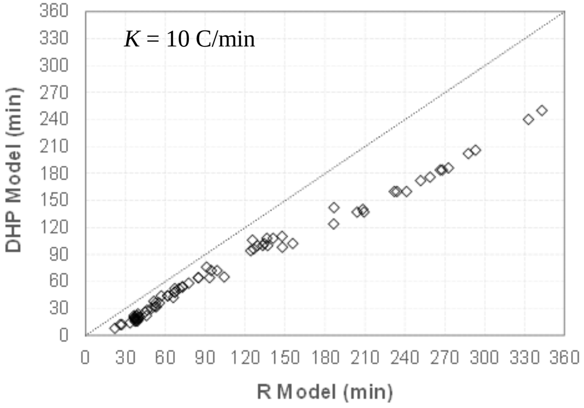
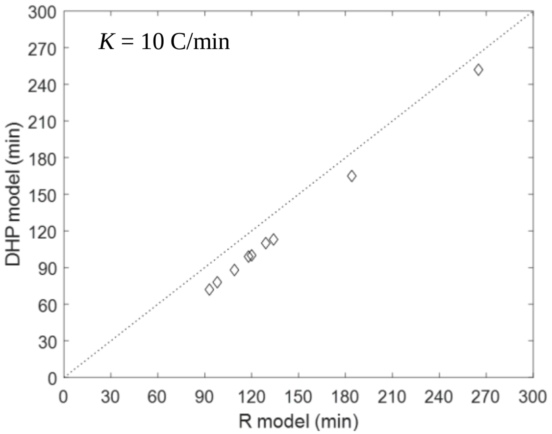
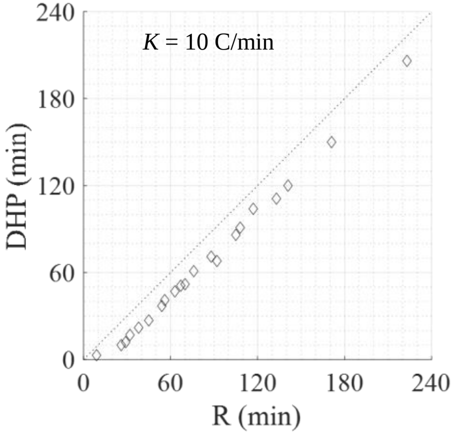
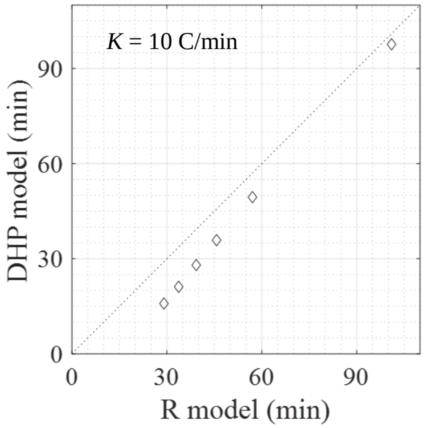


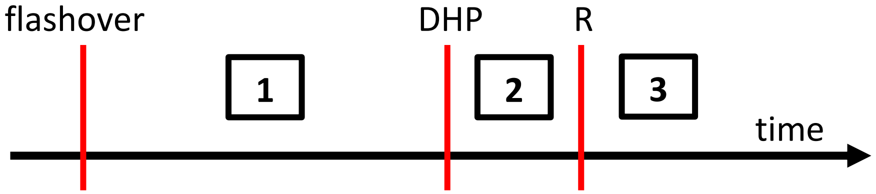
PC slabs (Maluk et al., 2015)



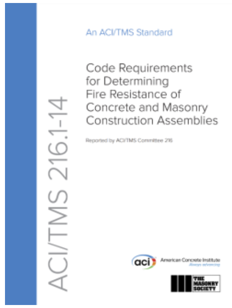








Design methods for burnout resistance



Tabulated data for burnout resistance design

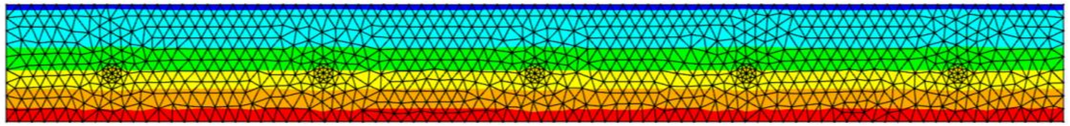
- Adjust values in ACI 216 to provide design solutions for *burnout resistance*

Minimum thickness for concrete floors

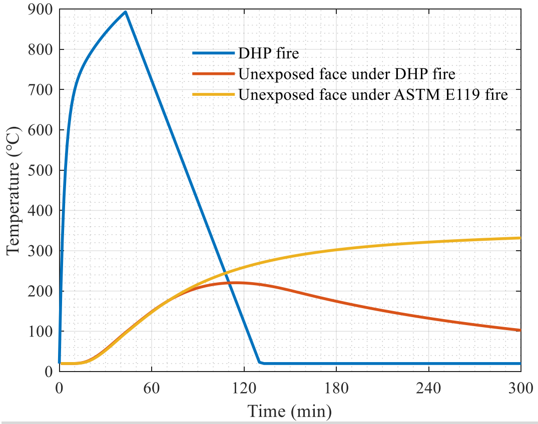
Fire resistance of single-layer concrete walls, floors, and roofs (from ACI 216)

Aggregate type	Minimum equivalent thickness for fire-resistance rating, mm				
	1 hour	1-1/2 hours	2 hours	3 hours	4 hours
Siliceous	90	110	125	155	175

Numerical modeling including cooling phase



Check thermal insulation criteria



Heat transfer continues during cooling

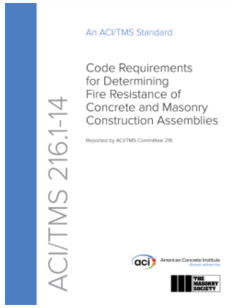
Burnout-resistance rating (fire barrier criteria) as a function of the equivalent thickness, mm

R rating	**1 hour**	**1-1/2 hours**	**2 hours**	**3 hours**	**4 hours**
thickness (mm)	90	110	125	155	175
R (min)	64	93	120	185	240
DHP (min)	43	76	108	183	240

Minimum equivalent thickness for burnout-resistance rating (fire barrier criteria), mm

DHP rating	**1 hour**	**1-1/2 hours**	**2 hours**	**3 hours**	**4 hours**
thickness (mm)	105	120	130	155	175
R (min)	86	111	130	185	239

Design methods for burnout resistance



Minimum cover for concrete floors

Minimum cover in concrete floors and roof slabs (from ACI 216)

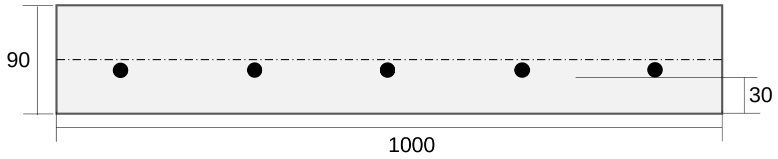
Aggregate type	Cover*† for corresponding fire resistance, mm					
	Restrained	Unrestrained				
	4 or less	1 hour	1-1/2 hours	2 hours	3 hours	4 hours
Nonprestressed						
Siliceous	20	20	20	25	30	40
Carbonate	20	20	20	20	30	30
Semi-lightweight	20	20	20	20	30	30
Lightweight	20	20	20	20	30	30
Prestressed						
Siliceous	20	30	40	45	60	70
Carbonate	20	25	35	40	55	55
Semi-lightweight	20	25	35	40	50	55
Lightweight	20	25	35	40	50	55

*Shall also meet minimum cover requirements of 4.3.1.

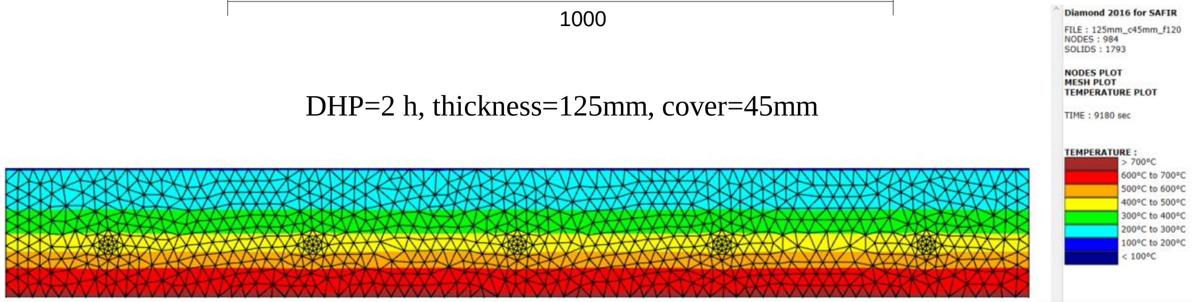
†Measured from concrete surface to nearest surface of longitudinal reinforcement.

Minimum cover for burnout-resistance rating in prestressed concrete slabs, mm. Siliceous aggregates concrete. Thickness satisfies heat-transmission end point for burnout resistance.

DHP Rating	1 hour	1-1/2 hours	2 hours	3 hours	4 hours
Thickness (mm)	105	120	130	155	175
Cover for R (mm)	30	40	45	60	70
Cover for DHP (mm)	30	40	50	NP	NP

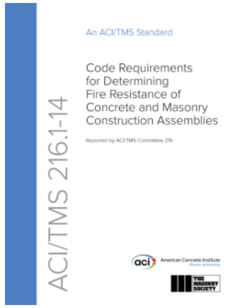


DHP=2 h, thickness=125mm, cover=45mm



- Tables derived for applied load ratio of 0.35 and cooling rate of 10 °C/min
- Finding minimum cover to maintain stability until full fire burnout
- Minimal design adjustment required

Design methods for burnout resistance



Minimum cover for concrete beams

Minimum cover in non-prestressed beams (from ACI 216).

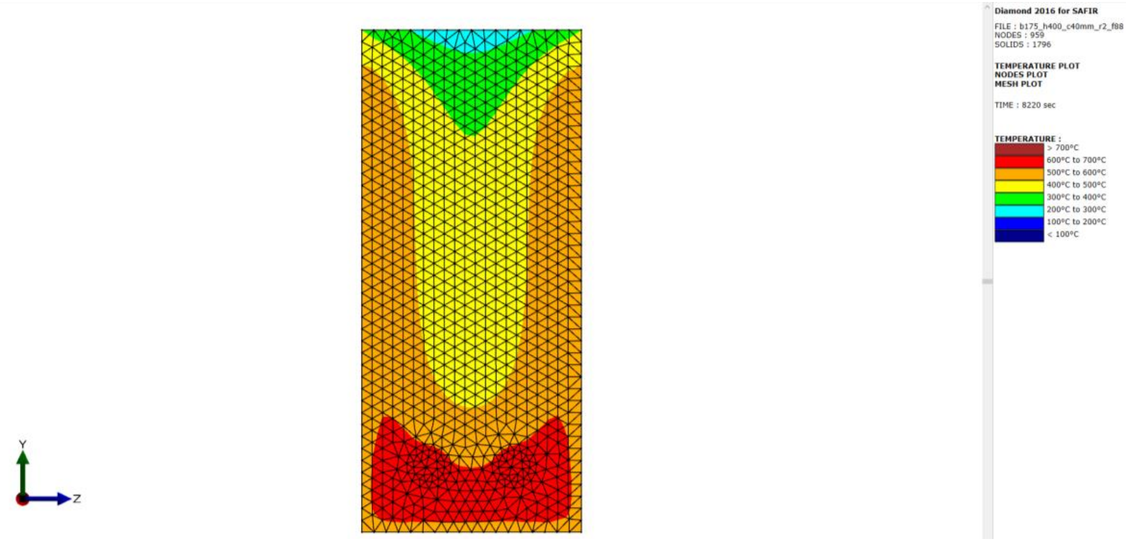
Restraint	Beam width, mm	Cover for corresponding fire-resistance rating, mm				
		1 hour	1-1/2 hours	2 hours	3 hours	4 hours
Restrained	125	20	20	20	25	30
	175	20	20	20	20	20
	≥250	20	20	20	20	20
Unrestrained	125	20	25	30	NP	NP
	175	20	20	20	45	75
	≥250	20	20	20	25	45

Note: NP = not permitted.

- Tables derived for a set of RC beams
- Their thermal-structural response is evaluated
- Minimum covers are determined for target DHP (burnout resistance) times

Minimum cover for fire-resistance and burnout-resistance ratings, non-prestressed unrestrained beams, in mm.

Beam width (mm)	Rating (min)	1 hour	1 ½ hour	2 hours
125	R	20	25	30
125	DHP	25	35	45
175	R	20	20	20
175	DHP	20	25	45
250	R	20	20	20
250	DHP	20	25	25



Temperature distribution at the time of failure for the fire with 88 minutes of heating phase, for the beam with width of 175 mm and cover of 40 mm

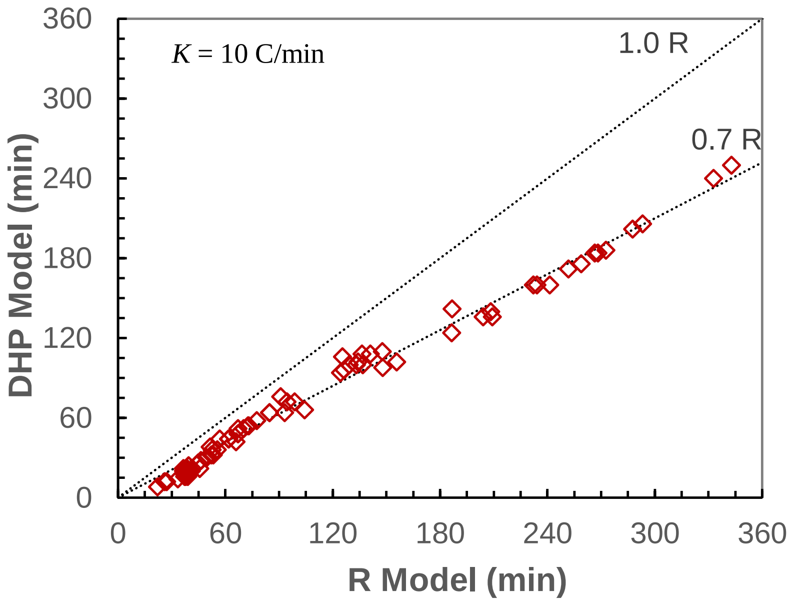
Design methods for burnout resistance

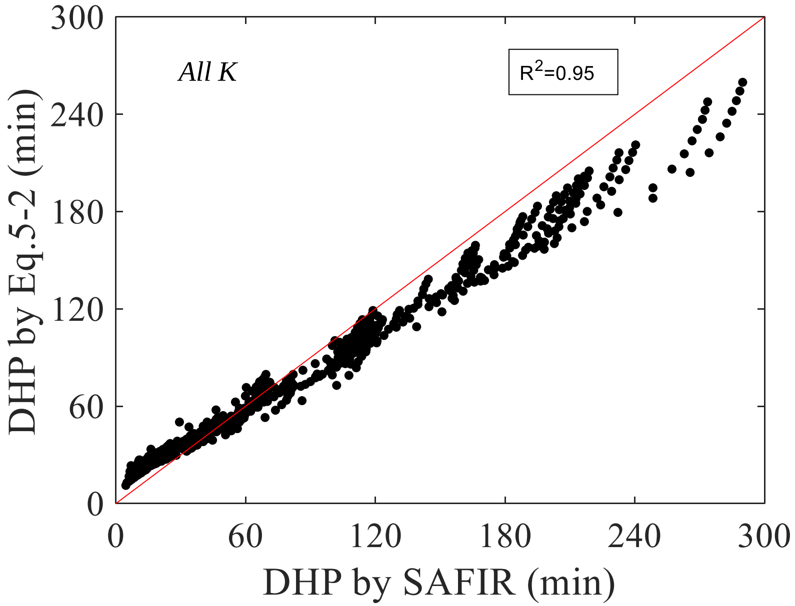
Regression equation for concrete columns

- The burnout resistance can be evaluated from the fire resistance

For 10 C/min cooling rate: $DHP = 0.72 \times R - 3.0$ (in min)

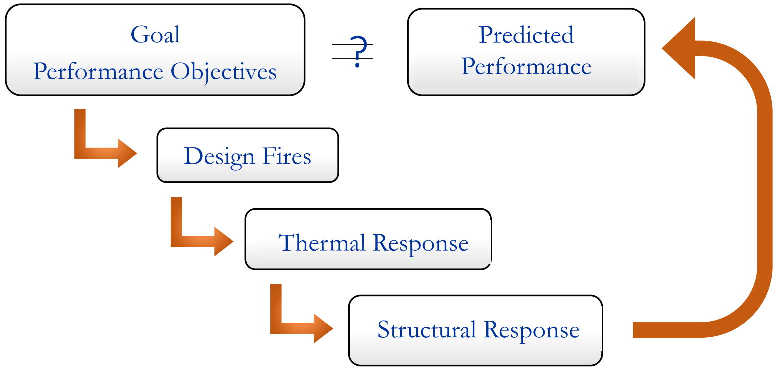
Function of cooling rate: $DHP = (0.7 \times R) \times (\frac{K}{10})^{0.2}$ (in min)





Performance-based fire design for concrete structures

- Determine performance objectives
  - ➢Some (stability to burnout, resilience) require evaluating response throughout the fire
- Determine design fires
  - ➢Based on compartment and fuel characteristics
  - ➢Will be different from the “standard” natural fire proposed here for benchmarking
- Determine the thermal-structural response of concrete members under design fire
  - ➢Thermal and mechanical properties tests provide data for cooling phase
  - ➢Transient FE models can be used with the cooling-appropriate material models



Conclusions

- Data on properties during and after cooling
  - Thermal properties are irreversible
  - Compressive strength further degrades during cooling compared to “hot” value
- Systematic numerical method to assess resistance to full burnout
  - Can rely on “standardized” natural fire exposure for comparability
  - This is a generic method for benchmarking, not meant to replace a PBSFD
- The burnout resistance (DHP) of a member is always shorter than R
  - Structural members can fail during the cooling phase of a fire
  - Slower cooling rates result in lower burnout resistance
  - Tabulated data and simple methods can be adapted to account for the cooling effects
- Burnout resistance as a complementary metric to comparatively assess the fire performance of structural members and raise attention to effects of cooling phase

Behavior and Design of Concrete Structures Under Natural Fires

Thank you for your attention

Thank you to ACI Foundation, to ACI 216 committee members, and to the members of the Advisory Panel for the support

Thomas Gernay, Johns Hopkins University
Patrick Bamonte, Polytechnic Milan

ASCE/SEI Manual of Practice No. 138:
Performance-Based Fire Design Guidance for Concrete Structures

Monday, March 28, 2022
Orlando, Florida

Extra slides

Plan of the presentation

1. Context and objectives of the project
2. Why assessing the response during the cooling phase of a fire?
3. Experiments on concrete behavior during heating-cooling
4. Numerical analysis of concrete members under natural fire
5. Design methods for burnout resistance
6. Conclusions and recommendations

Task 1 – Specimens

- Compressive strength: 30 specimens (∅ = 100 mm, h = 250 mm) per mix
  - 10 test modalities
  - 3 specimens for repeatibility

- Thermal diffusivity: 4 (+1) specimens (∅ = 100 mm, h = 300 mm) per mix
  - 2 thermal cycles
  - 2 specimens for repeatibility

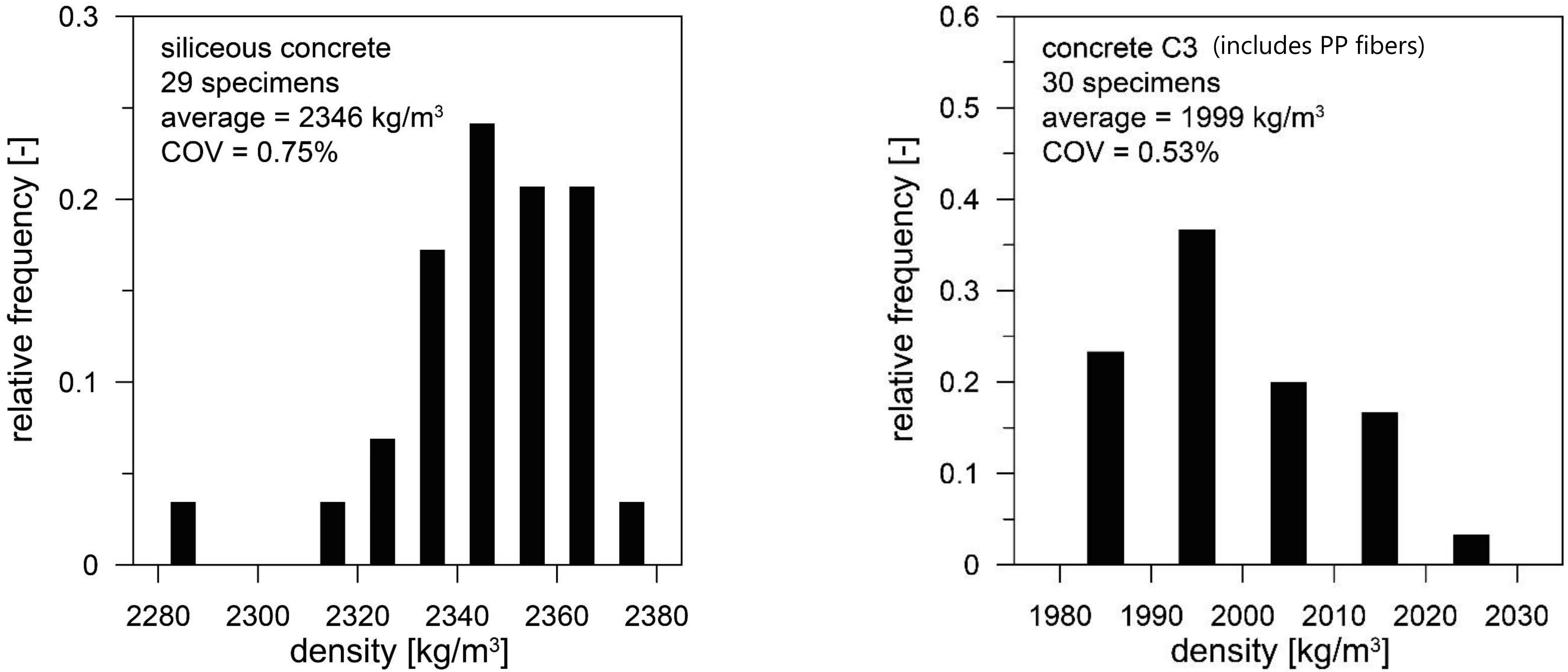
- Thermal dilation: 4 specimens (∅ = 80 mm, h = 200 mm) per mix
  - 2 thermal cycles
  - 2 specimens for repeatibility

	Mix 1 (S)	**Mix 2 (C1)**	**Mix 3 (C2)**	**Mix 4 (C3)**
casting date	8 Sep 2020	23 Oct 2020	11 Jan 2021	11 Jan 2021
aggregate	siliceous	calcareous	calcareous	calcareous
sand (0-4 mm)	965/990 kg			
gravel (4-10 mm)	695/720 kg			
cement (CEM I)	350 kg			
water	185 liters			
superplasticizer	1.0%-1.15%			
PP fibers	NO	YES	NO	YES

Concrete mixes – Mix proportions

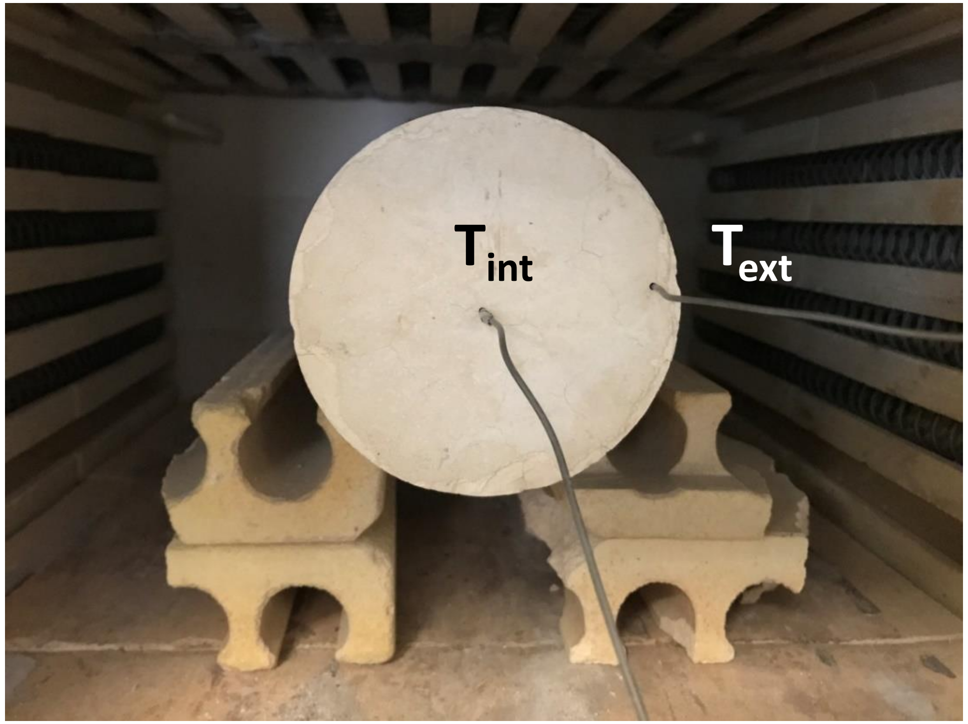
	Mix 1 (S)	Mix 2 (C1)	Mix 3 (C2)	Mix 4 (C3)
casting date	09/08/2020	10/23/2020	11/01/2021	26/01/2021
aggregate	siliceous	calcareous	calcareous	calcareous
sand (0-4 mm) [kg]	965	973	1071	1060
gravel (4-10 mm) [kg]	695	819	771	771
cement (CEM I) [kg]	350	350	350	350
water [l]	185	149	100	120
superplasticizer [%]	1.0	1.15	1.15	1.15
PP fibers	-	yes	-	yes
compressive strength [MPa]	34.4	29.5	47.5	31.3

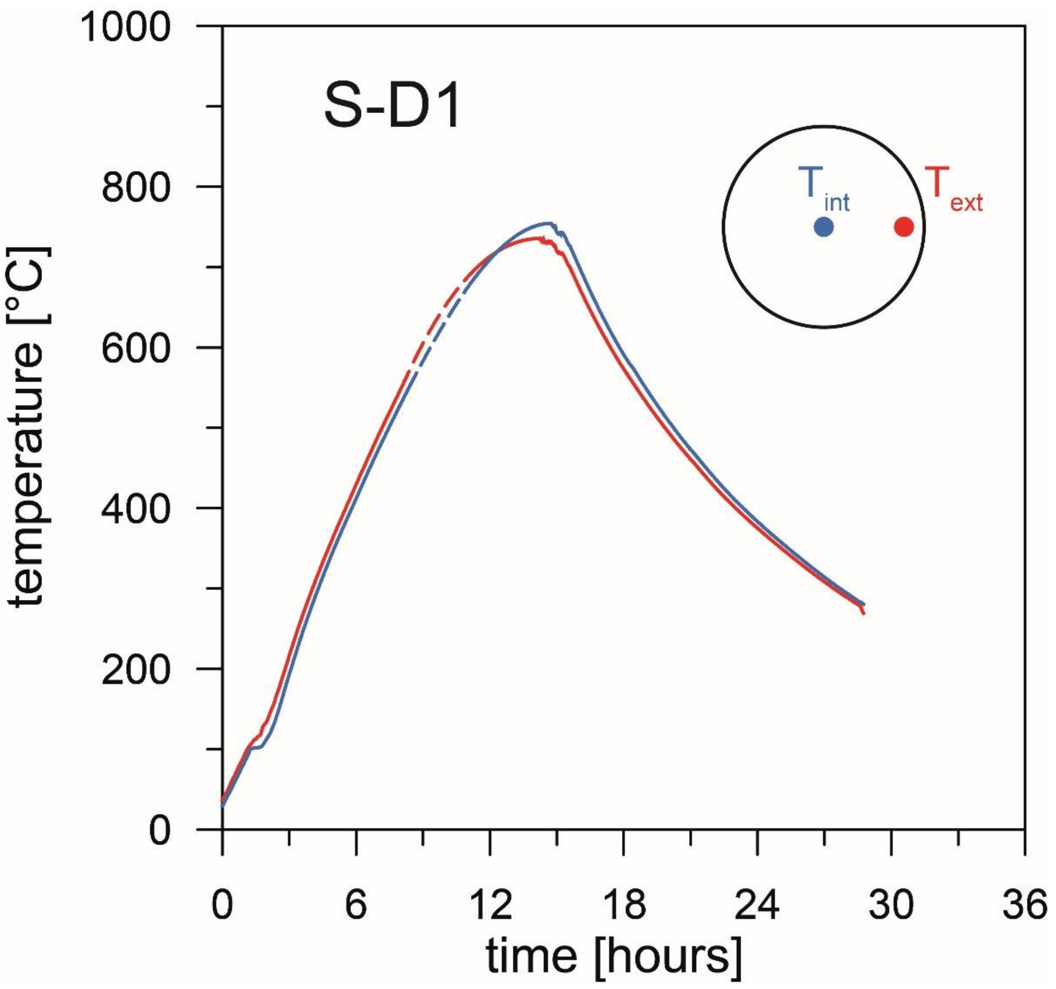
Concrete mixes – Quality control



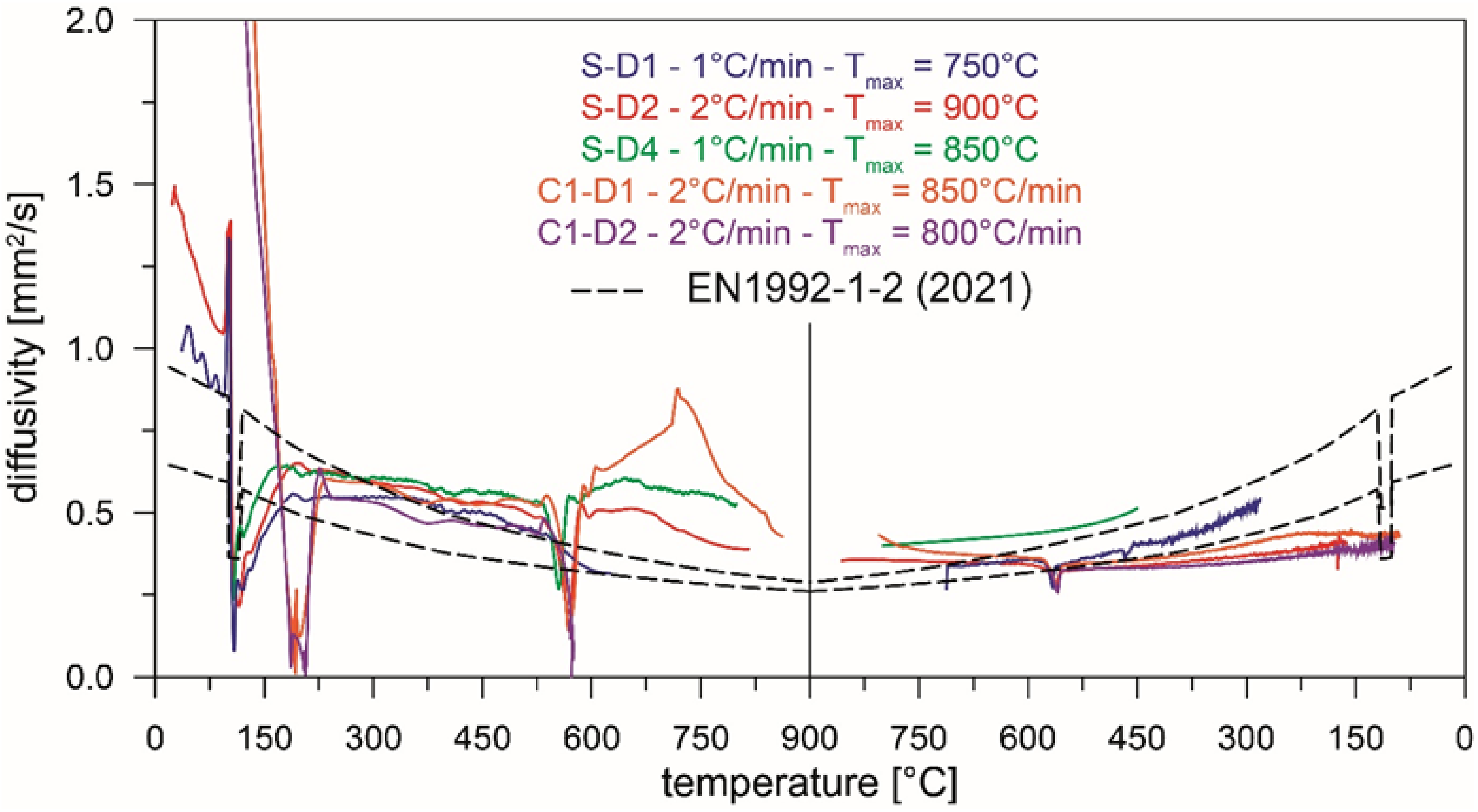
Visual inspection; weighing; density measurements (coefficient of variation < 1%)

Test results – Temperature measurements





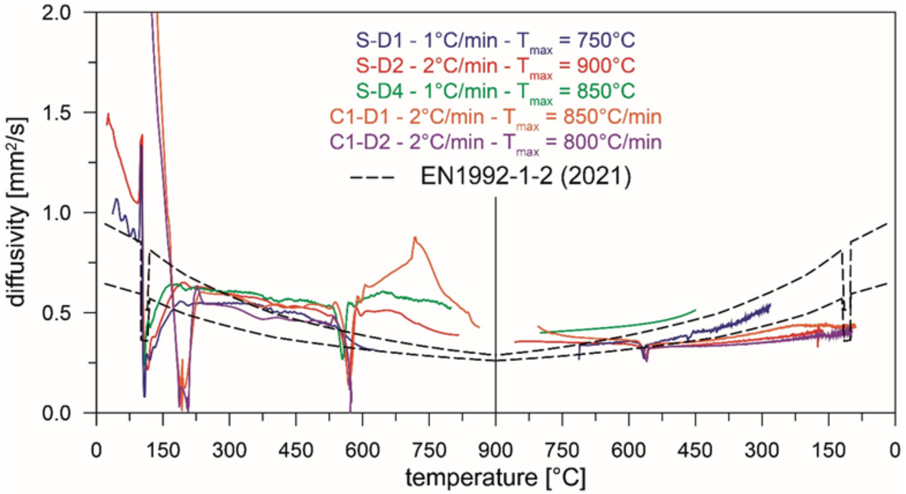
Test results – Thermal diffusivity (all specimens)

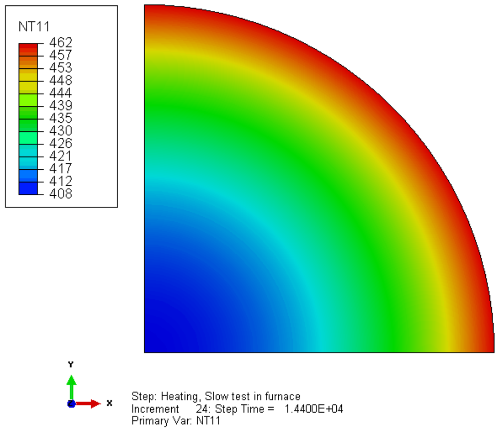


Thermal diffusivity is irreversible in cooling

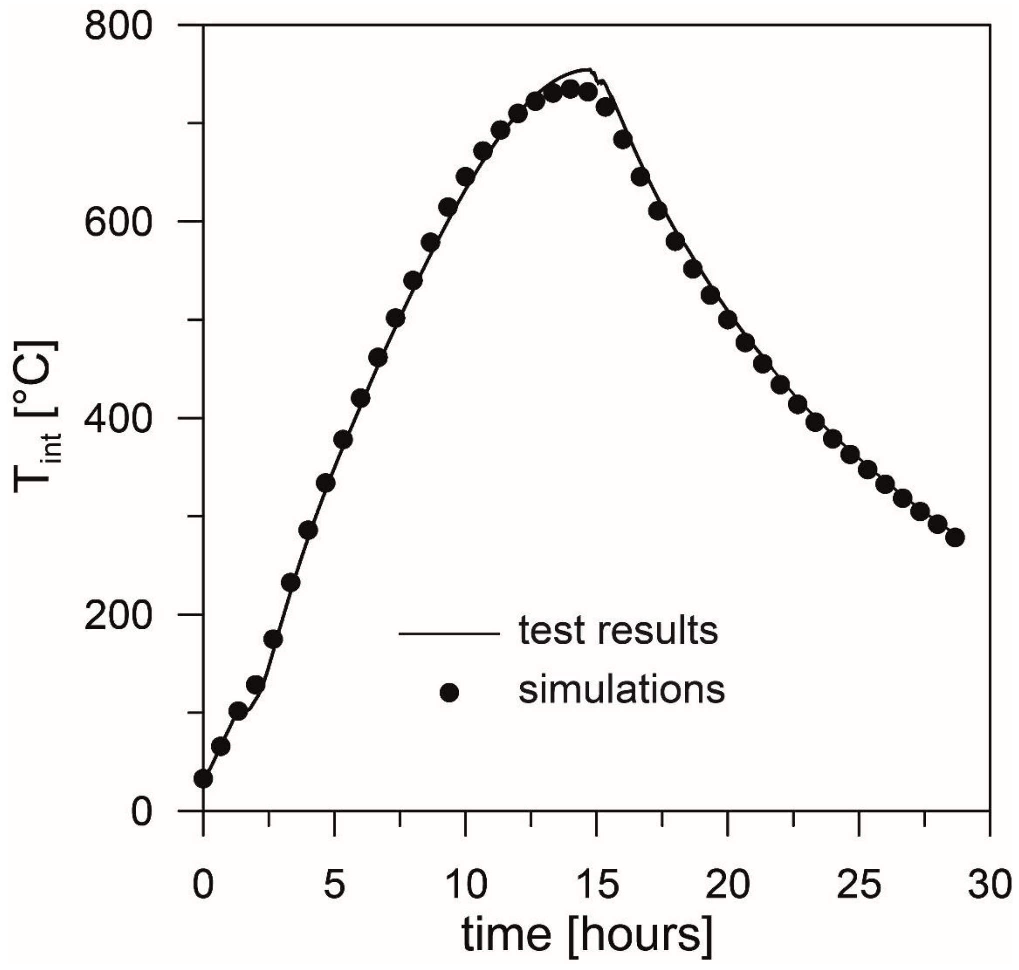
Numerical validation of diffusivity measurements

- Thermal diffusivity is the main parameter governing <u>heat transfer</u> inside a solid body by <u>conduction</u> during a transient state.
- From the thermal tests, specimen temperatures are measured: thermocouple TC1 (T_{ext}) and thermocouple TC2 (T_{int}).
- Diffusivity is indirectly obtained from the experiments considering heat transfer.
- Numerical analyses are separately conducted for cross-validation of the diffusivity: simulated temperatures (using the experimental diffusivity) are compared with measured temperatures.

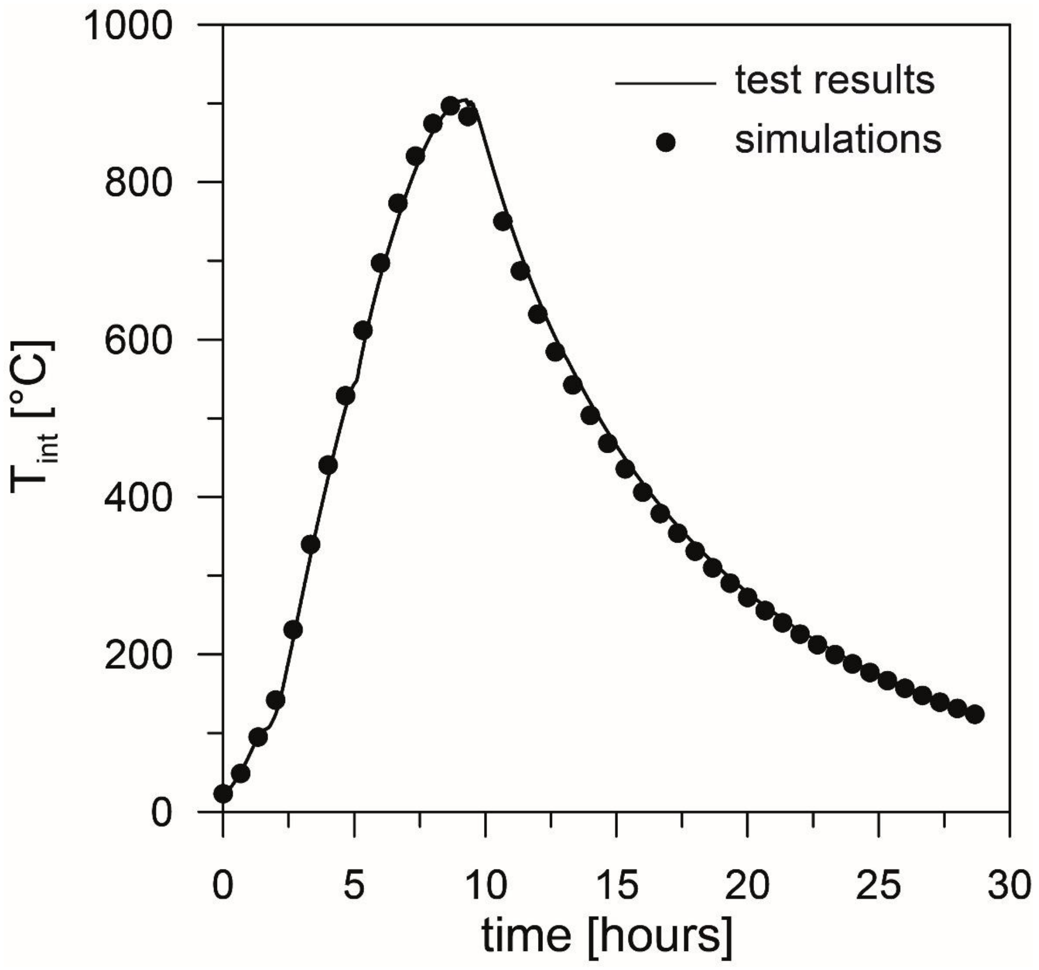




Numerical validation of diffusivity measurements



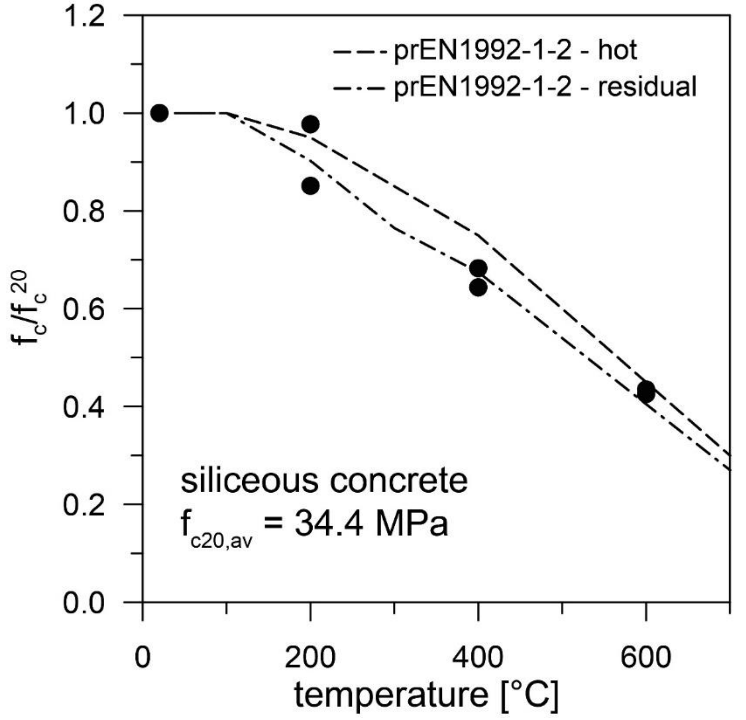
specimen **S-D1**

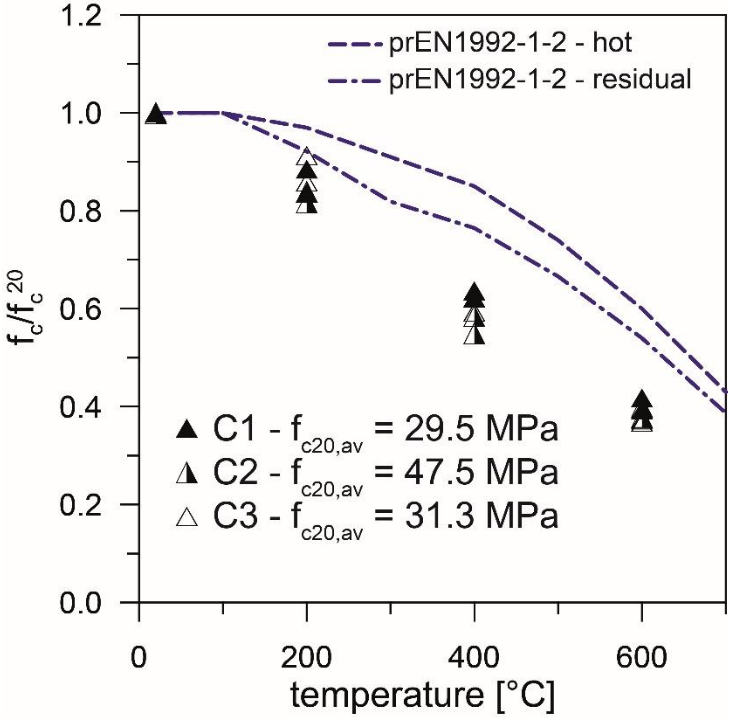


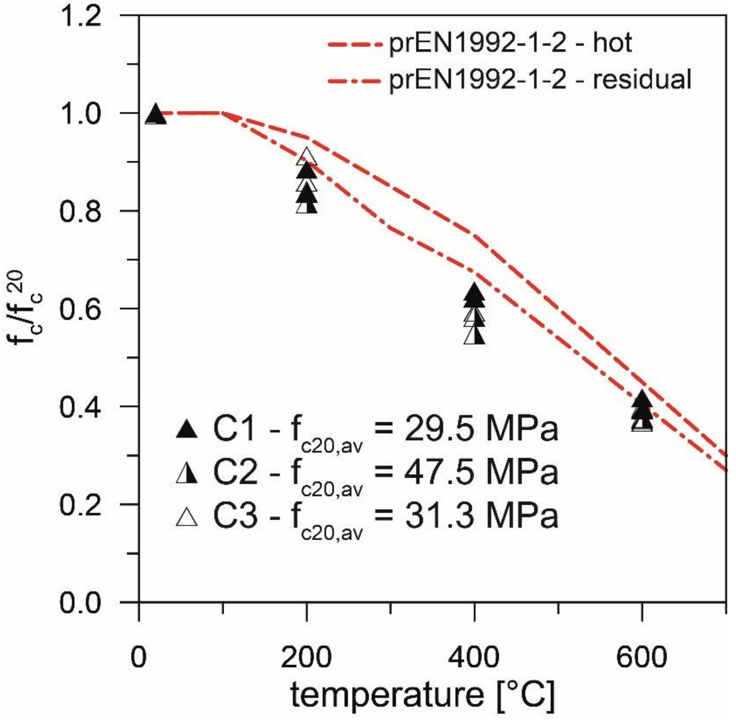
specimen **S-D2**

Residual tests – Overview

Residual tests – Compressive strength







Siliceous mix (S) vs standard curves for **SILICEOUS** aggregate

Calcareous mixes (C1-C2-C3) vs standard curves for **CARBONATE** aggregate

Calcareous mixes (C1-C2-C3) vs standard curves for **SILICEOUS** aggregate

Main outcomes of Task 1

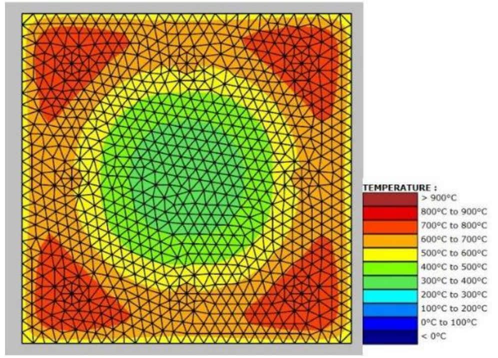
- The **thermal diffusivity** (indirectly) measured on the 4 mixes agrees **in the heating phase** with the two boundary curves provided by the Eurocode standard, especially below 500 °C
- The **thermal diffusivity in the cooling phase** clearly shows the **irreversibility** of the behavior: it is therefore reasonable to assume that, upon cooling, the diffusivity remains constant, and equal to the value attained at the maximum temperature reached during the thermal cycle
- The diffusivity which was indirectly measured during the tests was successfully **validated** by back-simulating the diffusivity tests, which (together with the agreement in heating with standard curves) supports the validity of the experimental procedure
- **Residual compressive strength** measured after heating to 200 °C, 400 °C, and 600 °C shows a greater loss of strength than the Eurocode provisions for elevated temperature (residual < hot)
- For **residual compressive strength**, the data for siliceous concrete agree with the tentative provisions given in prEN 1992-1-2. The data the other three concretes (calcareous with siliceous sand) reasonably agree with the code provisions for siliceous concrete but are lower than those for calcareous concrete.

Numerical modeling by FEM

Finite Element software SAFIR

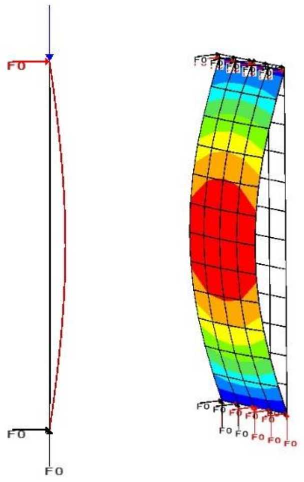
Thermal analysis

- Evaluate transient temperature distribution in the section
- 2D conductive elements + radiation and convection at the boundaries
- Material properties according to Eurocode 2, T-dependent, irreversible



Structural analysis

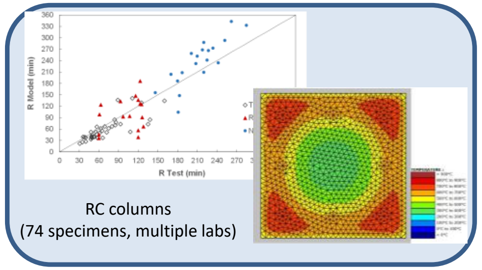
- Fiber-based beam FE (column, beam, slab) or shell elements (wall)
- Material properties according to Eurocode 2, T-dependent, irreversible



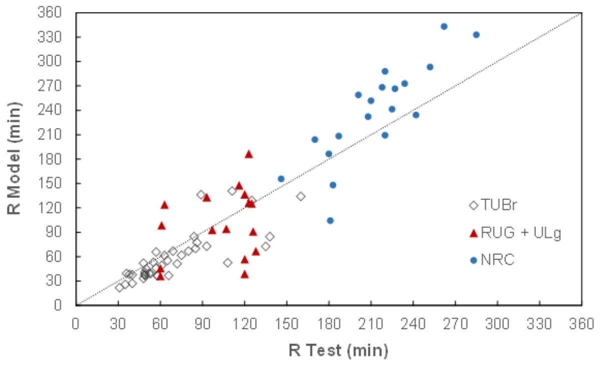
Analysis

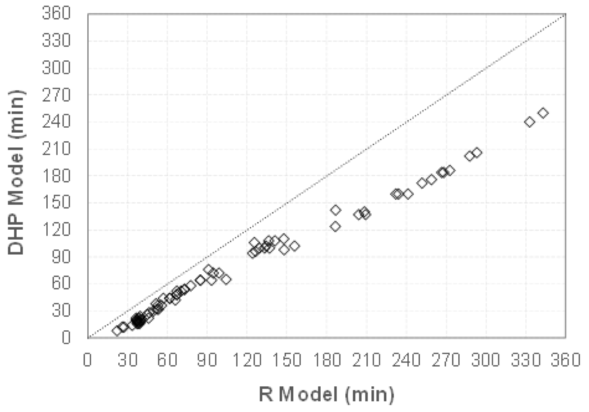
- Simulate the fire test for benchmarking
- Evaluate the DHP by iterative analyses, using the proposed “standard natural fires”

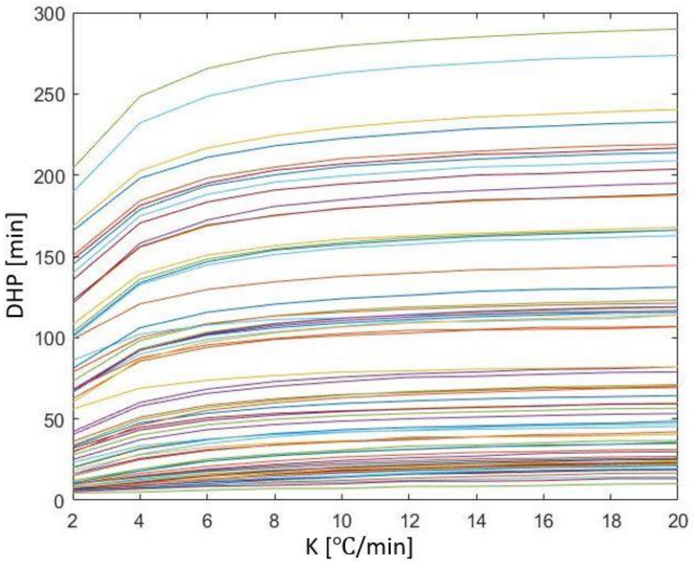
Reinforced concrete columns



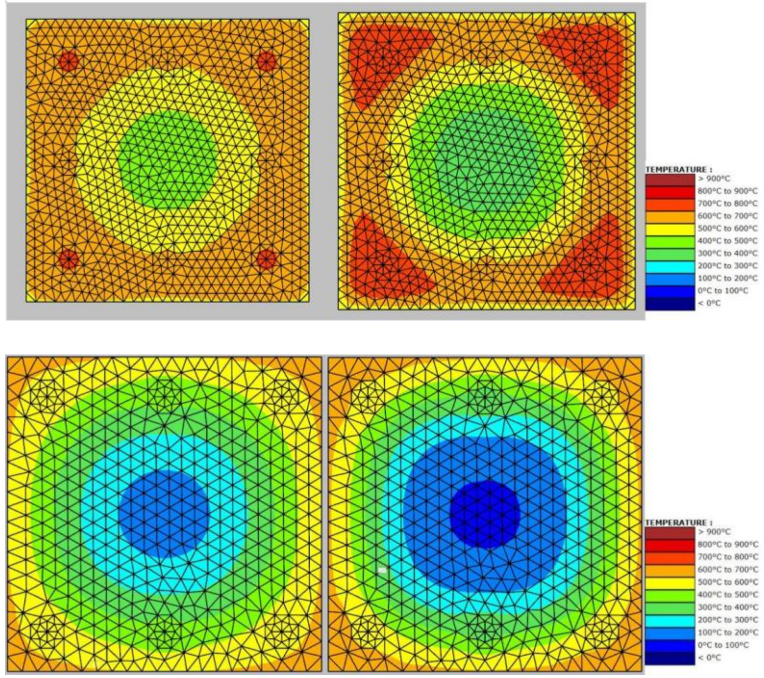
- 74 columns which were tested under standard fire
- Analyzed under standard fire and natural fires with 10 cooling rates *K* (~2-20 °C/min)







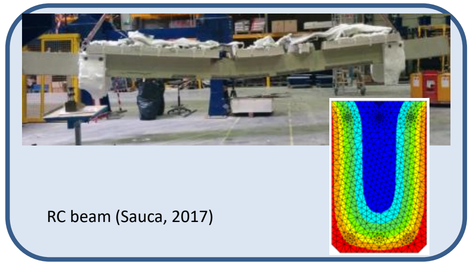
Each curve represents – for one column – the shortest duration of heating phase (following the ISO 834 curve) that leads to collapse of the column, as a function of the cooling rate in the decay phase



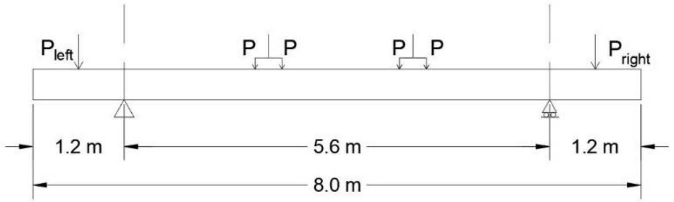
Temperature distribution at time of failure (different *K*)

Slower cooling (*K* ↘) increases the risk of failure during cooling (DHP ↘) for a given R-rating

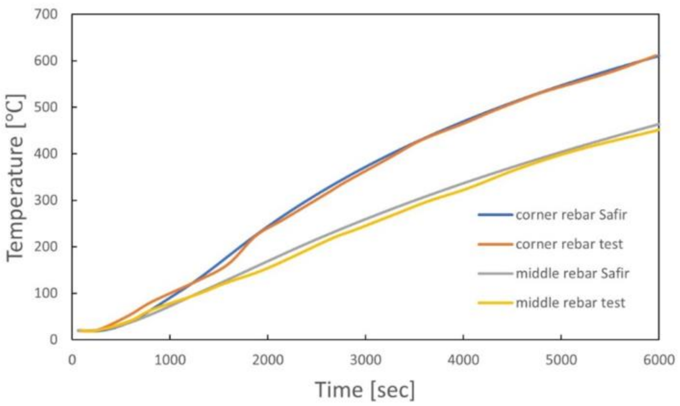
Reinforced concrete beams



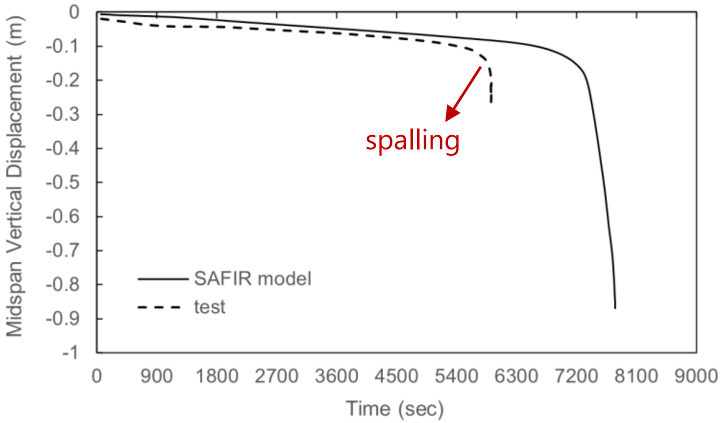
- Beam tested under standard fire in CERIB by Sauca (2017)
- **Benchmarked model against test**
- Analyzed prototype under standard natural fire, with 9 load ratios and 10 cooling rates *K* (~2-20 °C/min)



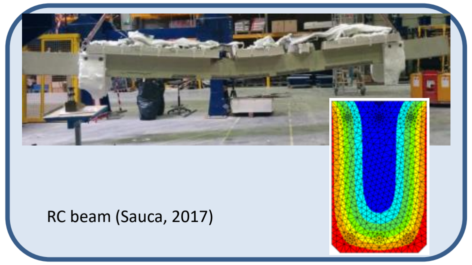
Comparison against test: temperatures



Comparison against test: displacements



Reinforced concrete beams



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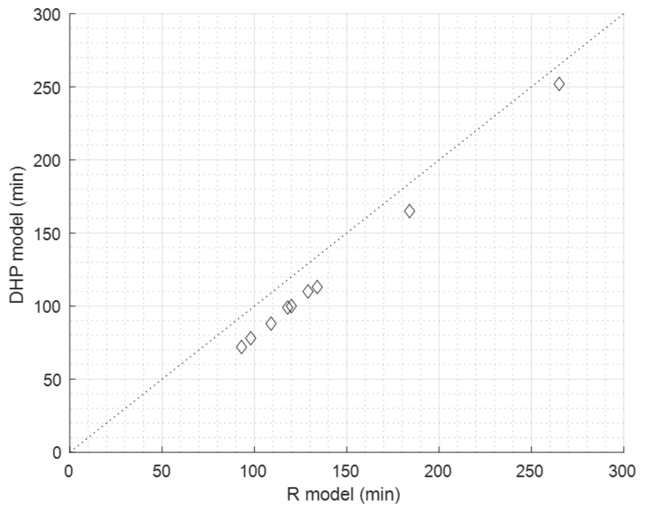
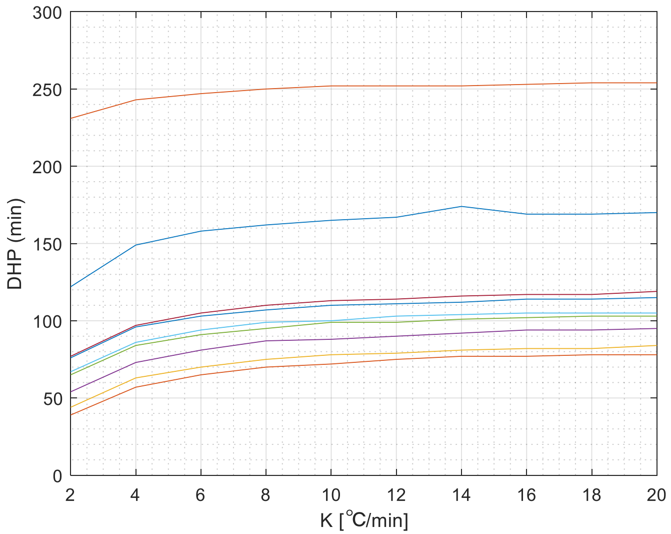
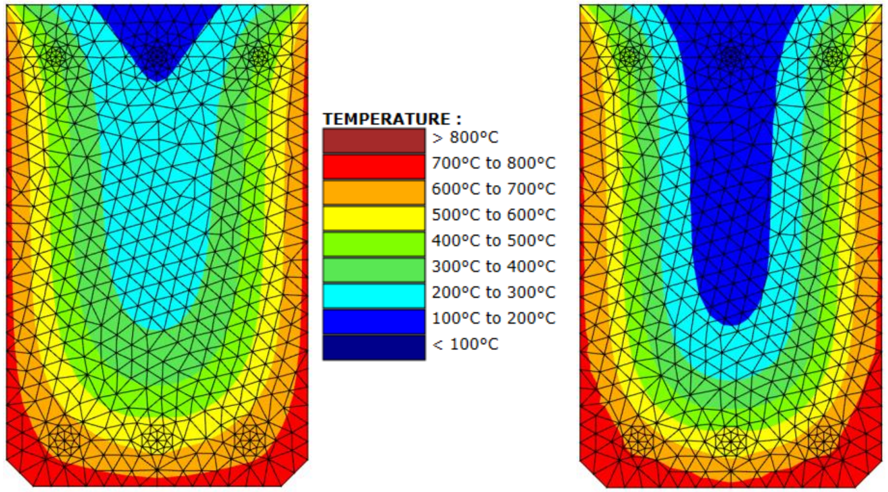


DHP with *K* = 10 C/min (EN Annex A)



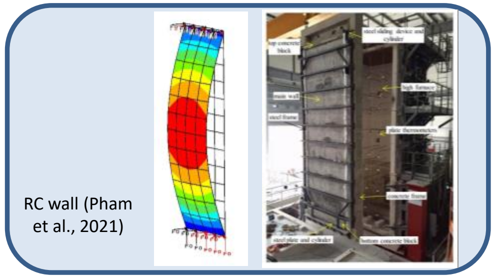
Effect of cooling rate *K*



Temperature distribution at time of failure (same beam, different *K*)

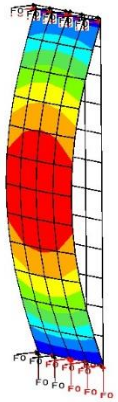
Behavior similar to columns, including linear relationship DHP-R and effect of cooling rate

Reinforced concrete walls

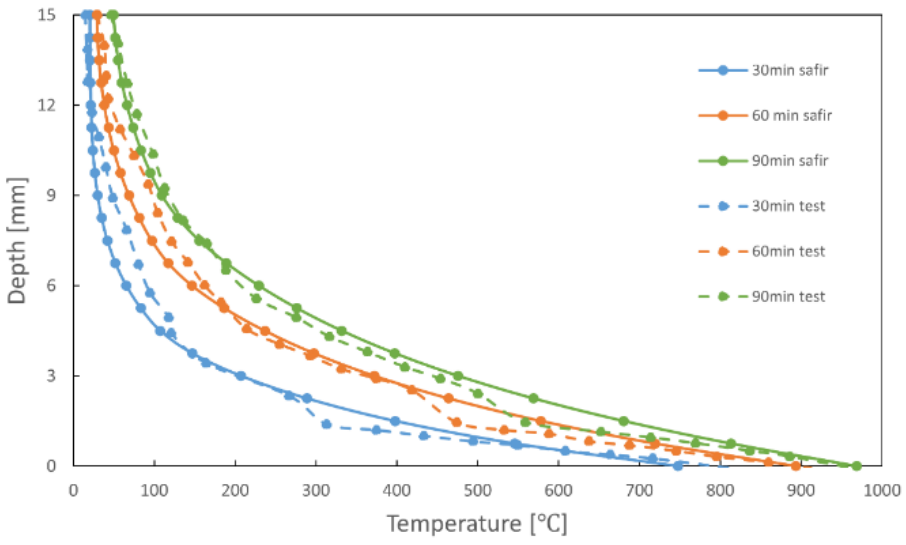


- Wall tested under standard fire by Pham et al. (2021)
- **Benchmarked model against test**
- Analyzed prototype under standard natural fire, with 2 heights and 10 load ratios

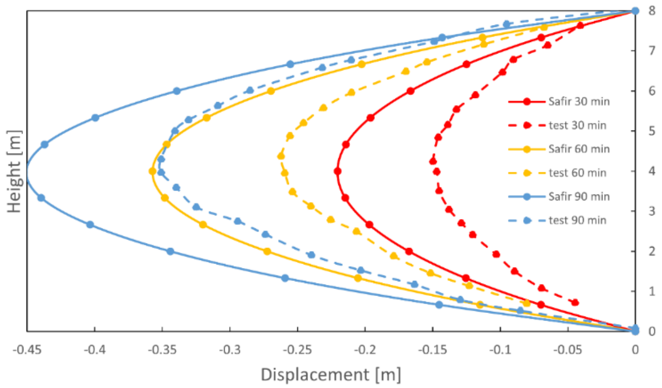
Shell finite element model

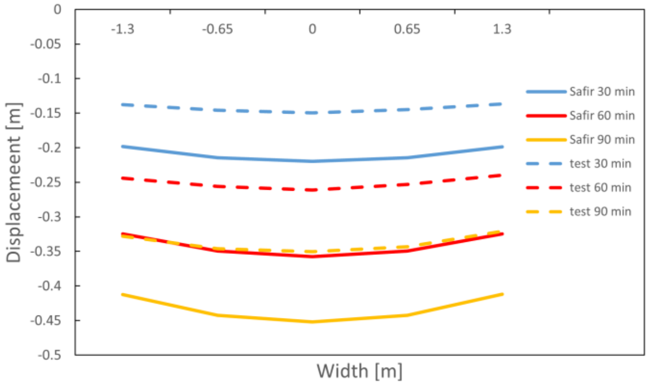


Comparison against test: temperatures

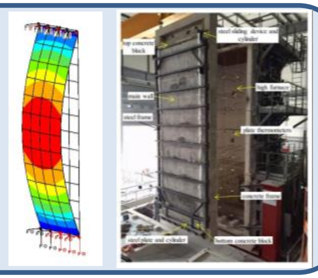


Comparison against test: displacements





Reinforced concrete walls



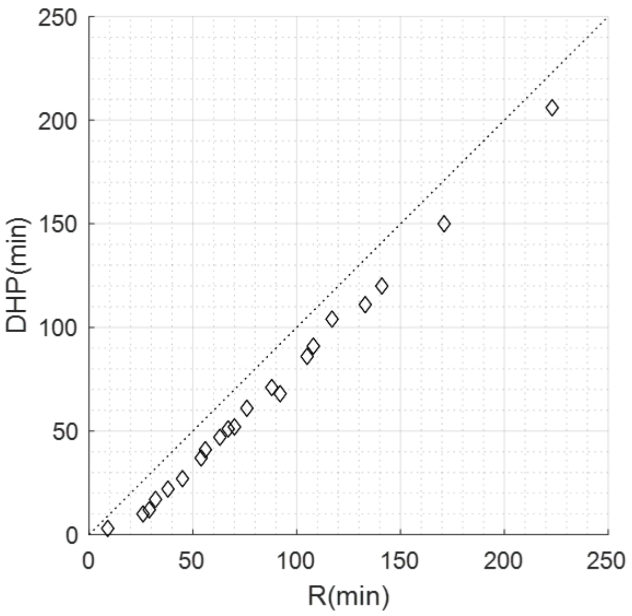
RC wall (Pham et al., 2021)

- Wall tested under standard fire by Pham et al. (2021)
- Benchmarked model against test
- **Analyzed prototype under standard natural fire**, with 2 heights and 10 load ratios

Results of fire resistance (R) and burnout resistance (DHP) for the studied cases

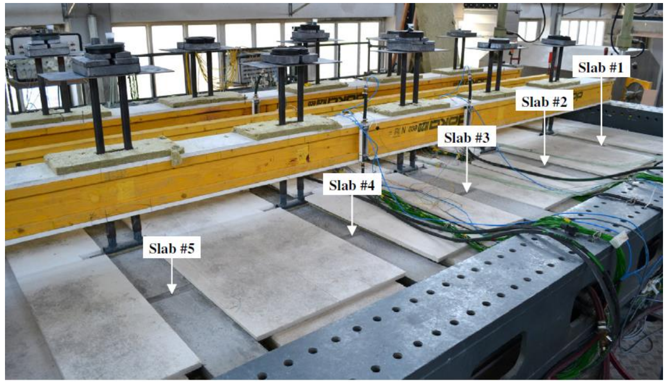
Height(m) \ Load ratio		0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
4.2	R(min)	223	171	141	117	105	92	76	70	63	56
	DHP(min)	206	150	120	104	86	68	61	52	47	41
8	R(min)	133	108	88	67	54	45	38	32	29	26
	DHP(min)	111	91	71	51	37	27	22	17	12	10

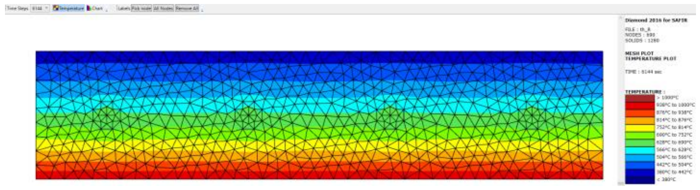
DHP with *K* = 10 C/min (EN Annex A)



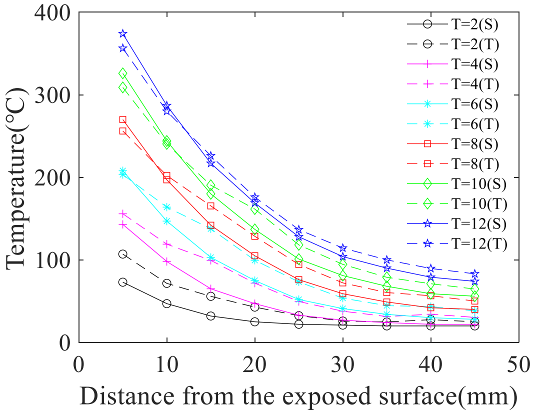
Prestressed concrete slab

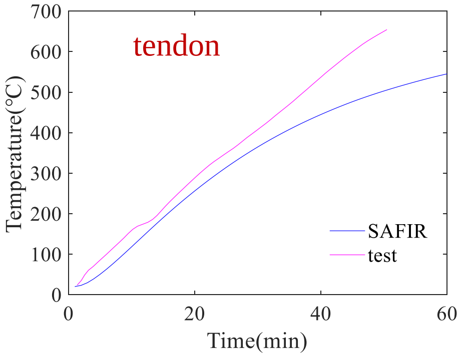
- Slab tested under standard fire by Maluk et al. (2015)
- **Benchmarked model against test** (note: modeled with prestressing steel instead of CFRP)
- Analyzed prototype under standard natural fire, with 6 load ratios and 10 cooling rates *K* (~2-20 °C/min)



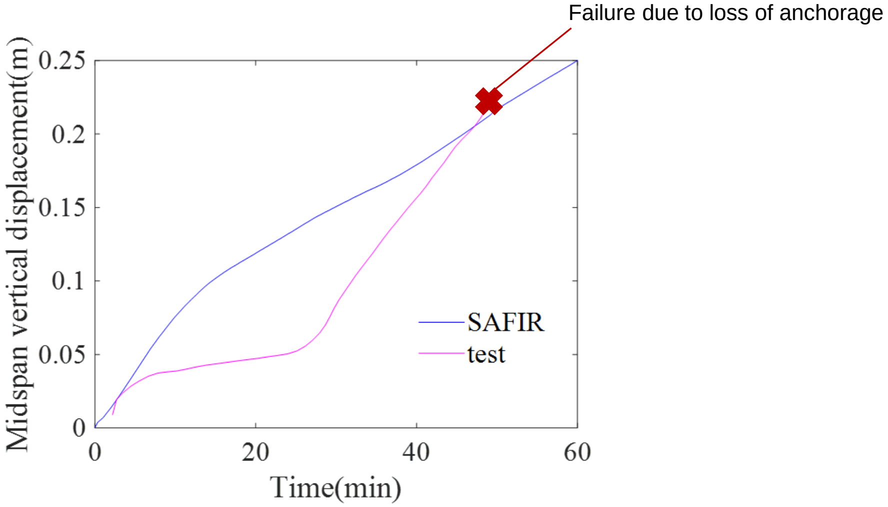


Comparison against test: temperatures





Comparison against test: displacements



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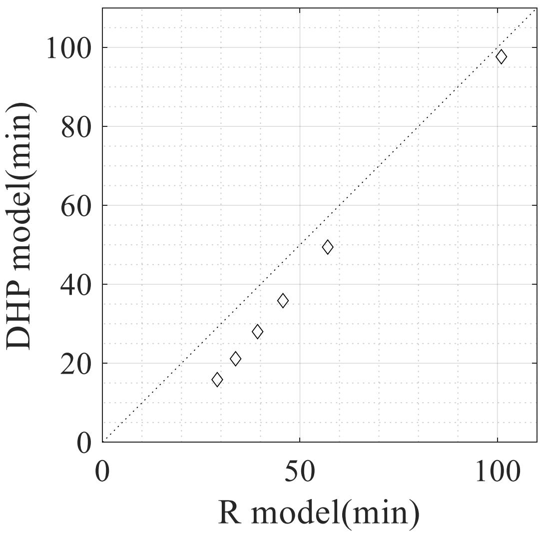
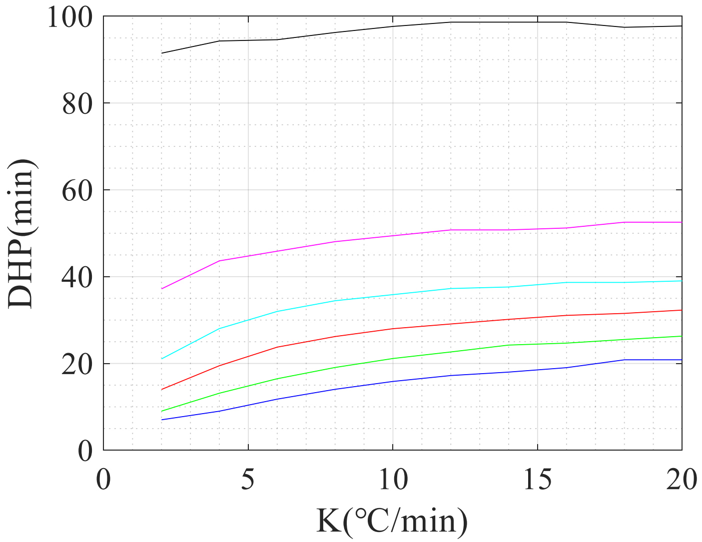
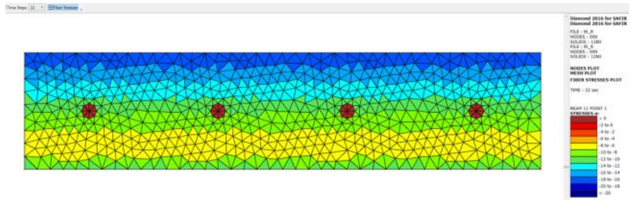


DHP with *K* = 10 C/min (EN Annex A)



Effect of cooling rate *K*



application of external loading – concrete in compression

The model can also simulate the fire response of prestressed concrete members