Co-funded by the Erasmus+ Programme of the European Union

SPECIAL MOBILITY STRAND

FIRE RESISTANCE OF STRUCTURES
Dr. Igor Džolev
Banja Luka, 10/03/2020

Asst. Prof. Igor Džolev, PhD, University of Novi Sad, Faculty of Technical Sciences
Full Prof. Đorđe Lađinović, PhD, University of Novi Sad, Faculty of Technical Sciences

Personal introduction

Assistant Prof. Igor Džolev PhD CE idzolev@uns.ac.rs

Civil Engineering

- Statics of structures
- Computational structural analysis
- Concrete bridges
- Steel bridges

Architecture

- Theory of structures

Disaster Risk Management and Fire Safety

- Risk Analysis Methods

Nonlinear thermo-mechanical analysis of the behavior of reinforced concrete frame structures subjected to fire

Co-funded by the Erasmus+ Programme of the European Union

Novi Sad, Open University Fire, 2000

April 6, 2000

April 6, 2000

present day

Co-funded by the Erasmus+ Programme of the European Union

Basic requirements

General objectives → Risk limitation

- Load bearing resistance needs to be provided for a specified period of time
- Generation and spread of fire and smoke need to be limited
- Spread of fire to neighbouring structures needs to be limited
- Safe evacuation of occupants need to be provided
- Safety of rescue teams needs to be taken into consideration

Methods of fire resistance assessment

- standard fire tests
- tabulated data (largely prescriptive but also increasingly based on calculations)
- simplified calculations (neglecting complex effects, such as thermal stresses)
- advanced calculations (largely performance based)
- full scale fire tests

Co-funded by the Erasmus+ Programme of the European Union

Basic requirements

Evaluation complexity levels

- Member analysis
- Substructure analysis
- Global structural analysis

Prescriptive and Performance based design

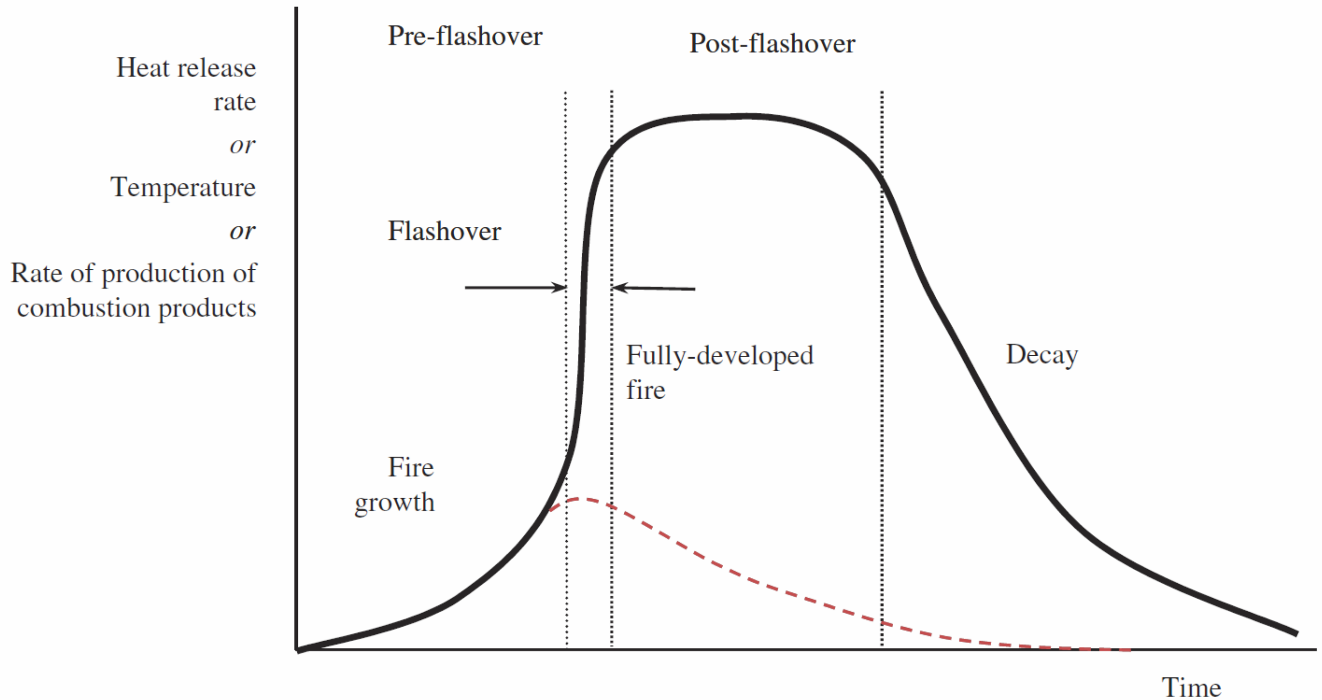
Modelling real fire to a realistic and conservative scenario

- Availability of combustible materials
- Ventilation conditions, in terms of oxygen delivery
- Physical characteristics of the space in which fire is initiated

Co-funded by the
Erasmus+ Programme
of the European Union

Fire action and fire models

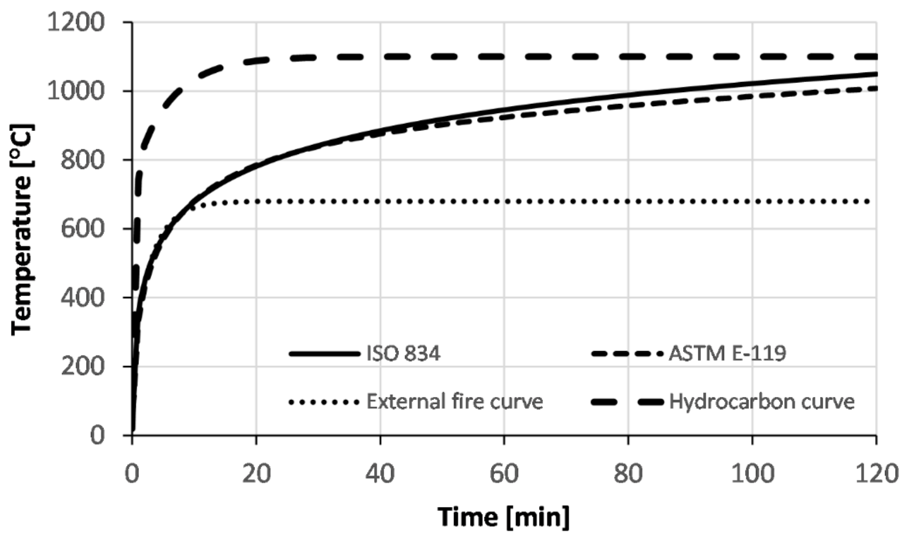
Fire - process of uncontrolled combustion endangering human lives and health, material goods and the environment



Fire action and fire models

Fire models

- Standard fire curves – ISO 834, ASTM E119, Hydrocarbon, External
- Parametric fire curves
- Advanced multi-zone and CFD models



Co-funded by the Erasmus+ Programme of the European Union

Fire action and fire models

Standard fire → Fire resistance measured in minutes

- **R - load bearing function** - ability of a structure or a member to sustain specified actions during the relevant fire, according to defined criteria
- **E - integrity function** - ability of a separating element, when exposed to fire on one side, to prevent the passage through it of flames and hot gases and to prevent the occurrence of flames on the unexposed side
- **I - insulation function** - ability of a separating element when exposed to fire on one side, to restrict the temperature rise of the unexposed face below specified levels

REI 60, EI 90, …

Co-funded by the Erasmus+ Programme of the European Union

Fire action and fire models

Parametric fire curves

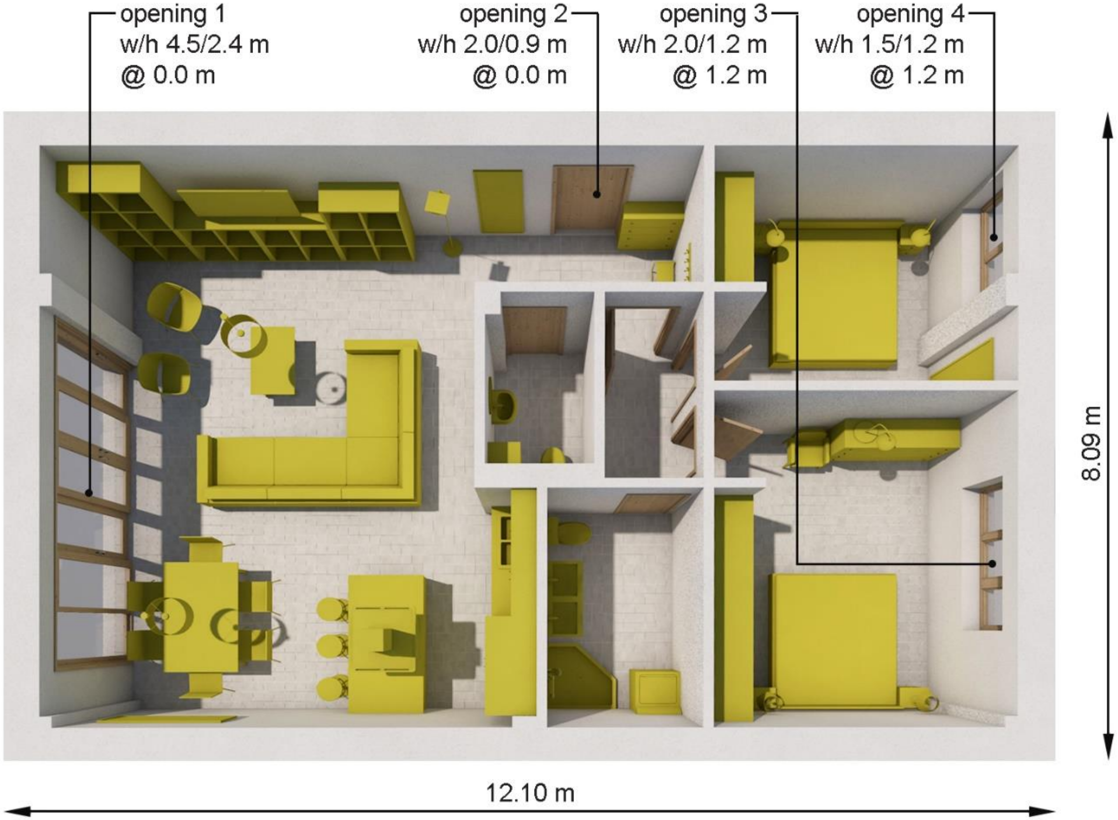
- More detailed assessment of a fire that could develop in a specific compartment
- Taking into account real geometric and material properties of the compartment, as well as ventilation conditions
- Include a cooling (decay) phase of the fire, providing temperature-time evolution during the whole course of fire

Multi-zone and CFD

- Based on mass and energy conservation laws
- Iterative procedure is needed, conditioning the use of these models to specialized computer software

Co-funded by the Erasmus+ Programme of the European Union

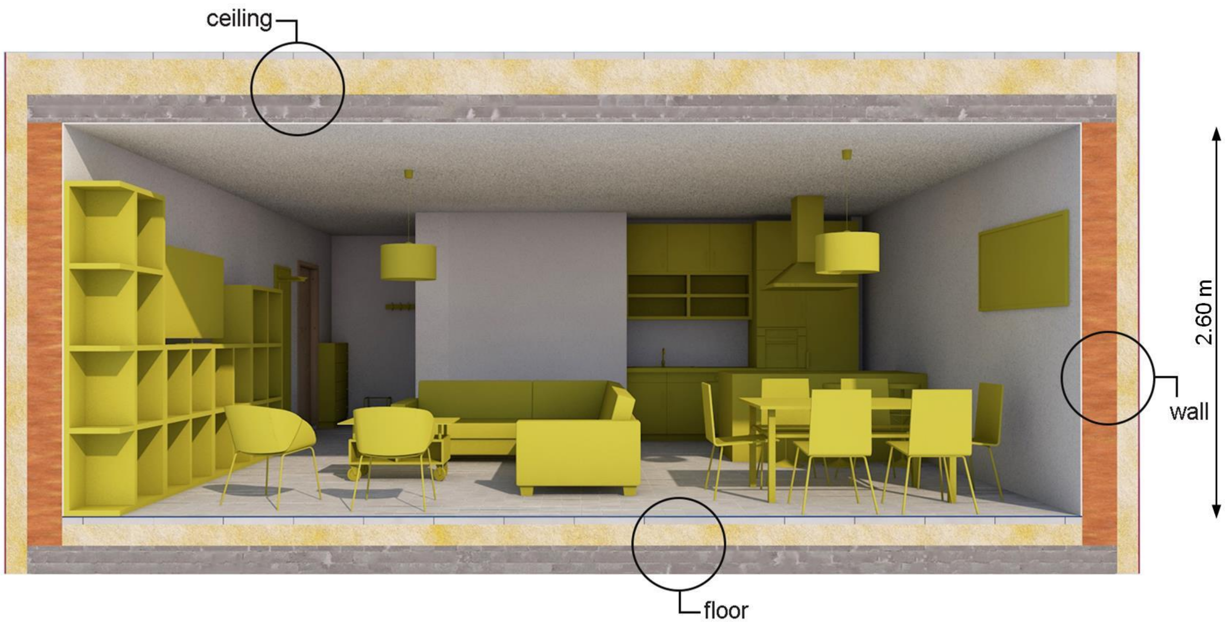
Fire action and fire models



Co-funded by the
Erasmus+ Programme
of the European Union

Fire action and fire models

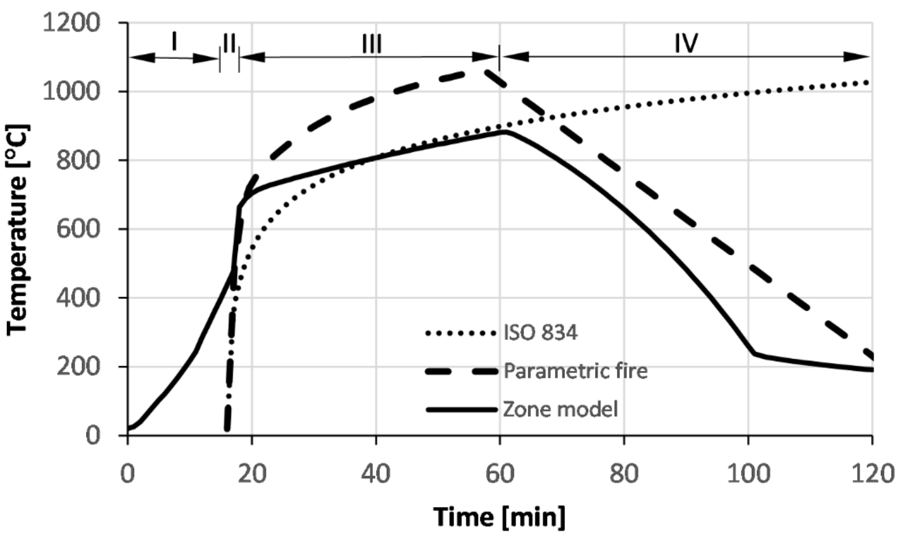
	Material
Floor	Ceramic tiles
	Concrete screed
	Rock wool
	Concrete
Ceiling	Mortar
	Concrete
	Rock wool
	Concrete screed
Wall	Mortar
	Thermo-block
	Rock wool
	Mortar



Co-funded by the Erasmus+ Programme of the European Union

Fire action and fire models

Temperature-time curves corresponding to analysed compartment



Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire analysis

Structural fire design analysis

- Selection of the relevant design fire scenarios
- Determination of the corresponding design fires
- Calculation of temperature evolution within the structural members
- Calculation of the mechanical behaviour of the structure exposed to fire

EN	Part	Title
EN 1990	n/a	Basis of structural design
EN 1991	1-2	Actions on structures - General actions - Actions on structures exposed to fire
EN 1992	1-2	Design of concrete structures - General rules - Structural fire design
EN 1993	1-2	Design of steel structures - General rules - Structural fire design
EN 1994	1-2	Design of composite steel and concrete structures - General rules - Structural fire design
EN 1995	1-2	Design of timber structures - General rules - Structural fire design
EN 1996	1-2	Design of masonry structures - General rules - Structural fire design
EN 1999	1-2	Design of aluminium structures - Structural fire design

Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire analysis

Numerical model complexity

- Based on fundamental physical behaviour
- Temperature-time field coupled with structural response material nonlinearity and degradation at elevated temperatures

General purpose programs - ANSYS, ABAQUS

Specialised programs - SAFIR, VULKAN, OPENSEES

Co-funded by the Erasmus+ Programme of the European Union

Structural fire analysis

Thermal response - Heat transfer

- Conduction
- Convection
- Radiation

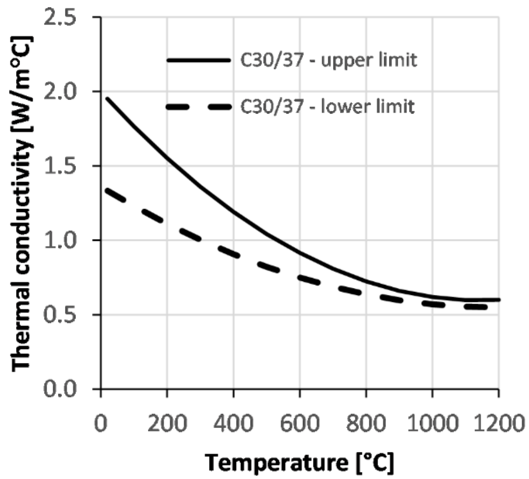
Input parameters

- Thermal conductivity
- Specific heat
- Density

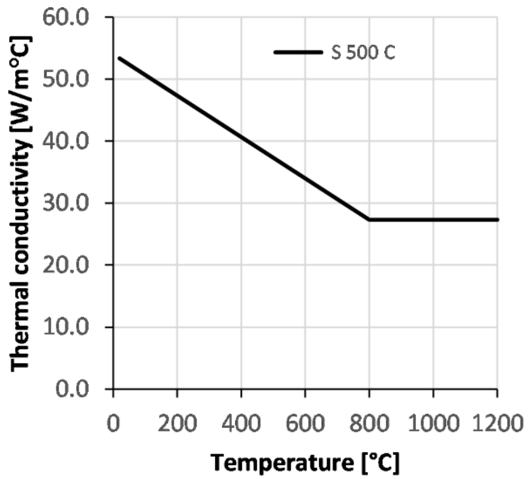
$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)=\rho c \frac{\partial T}{\partial t}$$

Co-funded by the
Erasmus+ Programme
of the European Union

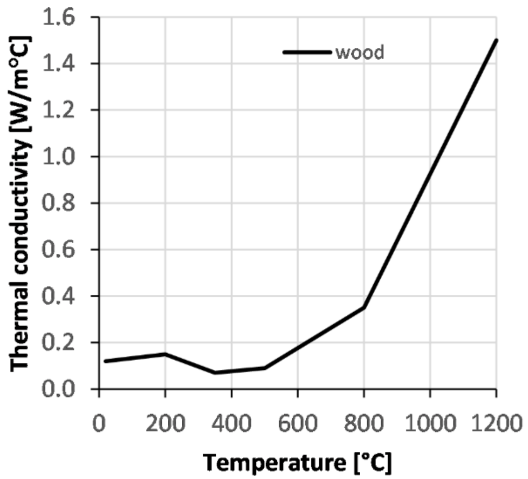
Thermal conductivity



concrete



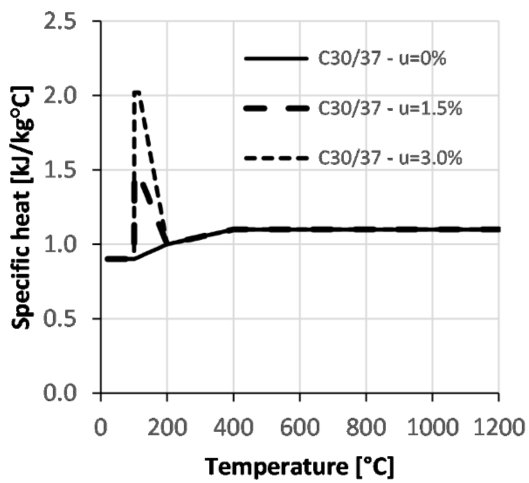
steel



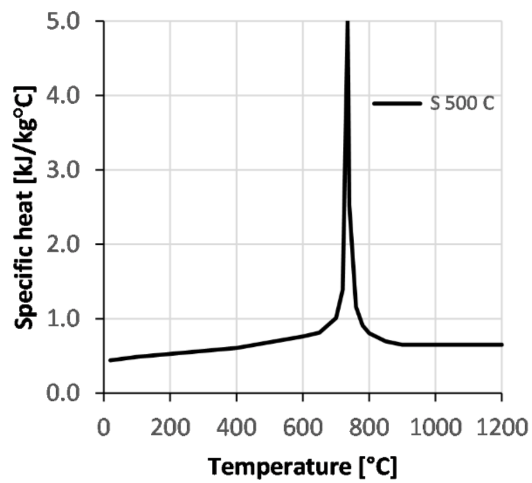
wood

Co-funded by the
Erasmus+ Programme
of the European Union

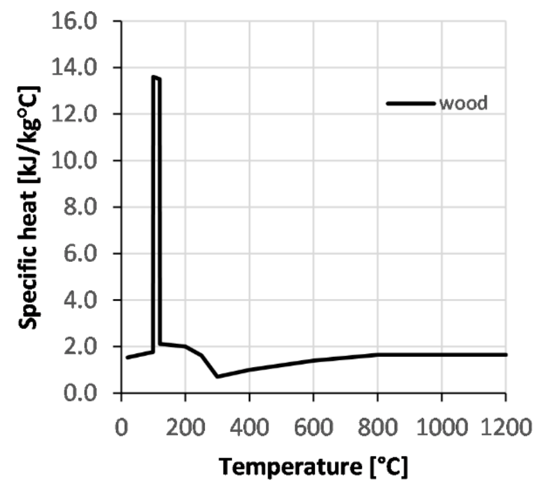
Specific heat



concrete



steel

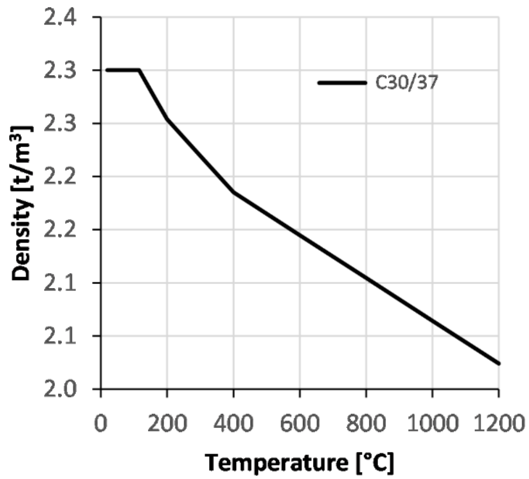


wood

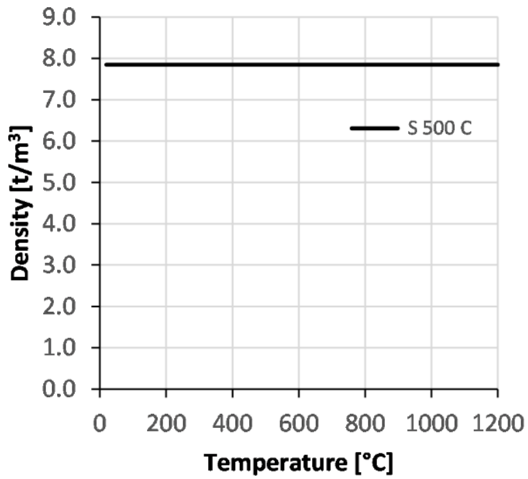
Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire analysis

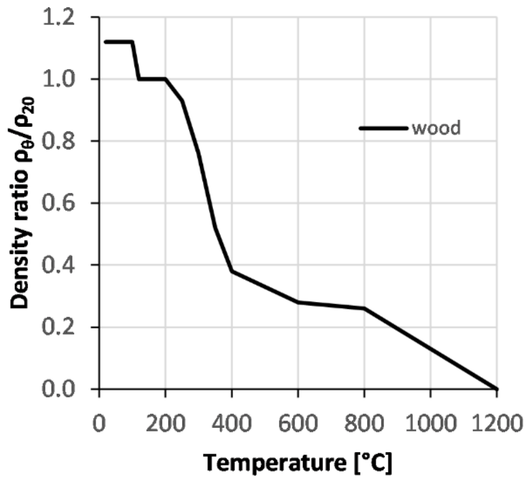
Density



concrete



steel



wood

Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire analysis

Mechanical response - Structural analysis

- Material nonlinearity
- Degradation at elevated temperatures

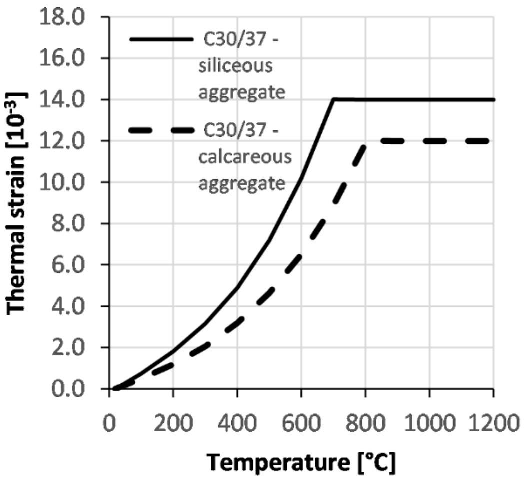
Temperature dependent properties

- Thermal strains
- Stress-strain relations

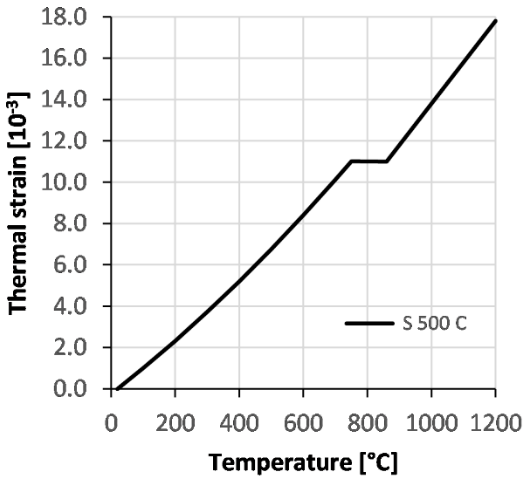
Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire analysis

Thermal expansion



concrete

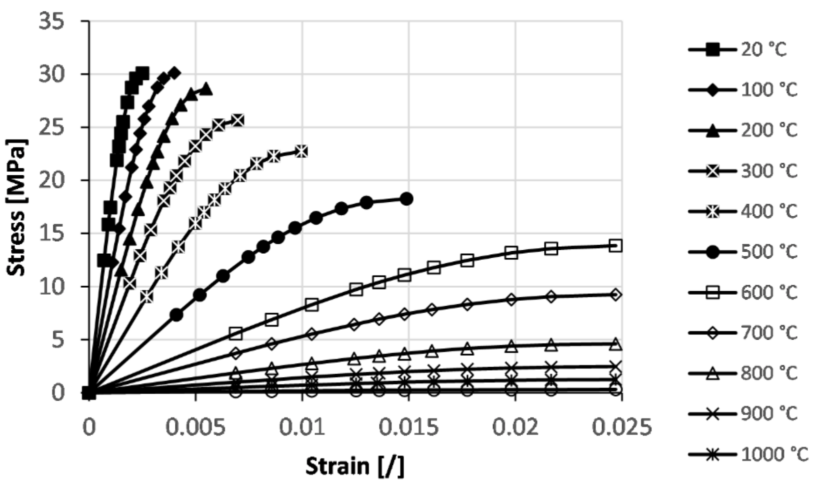


steel

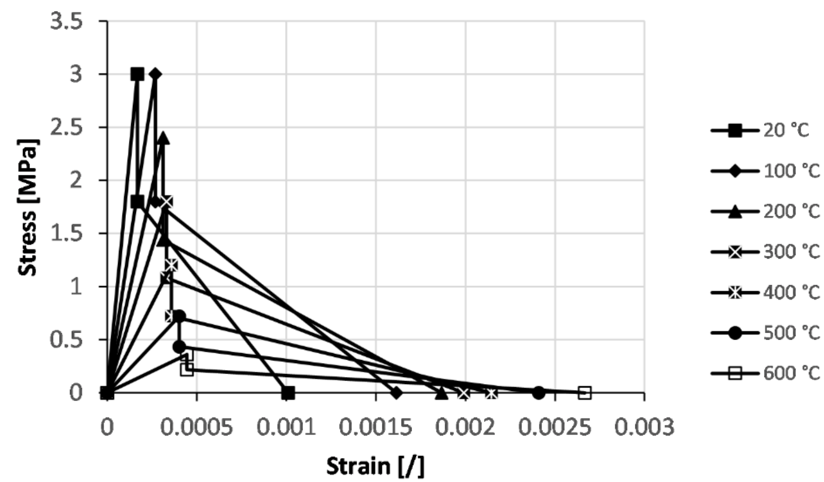
Co-funded by the Erasmus+ Programme of the European Union

Structural fire analysis

Stress-strain relations - Concrete



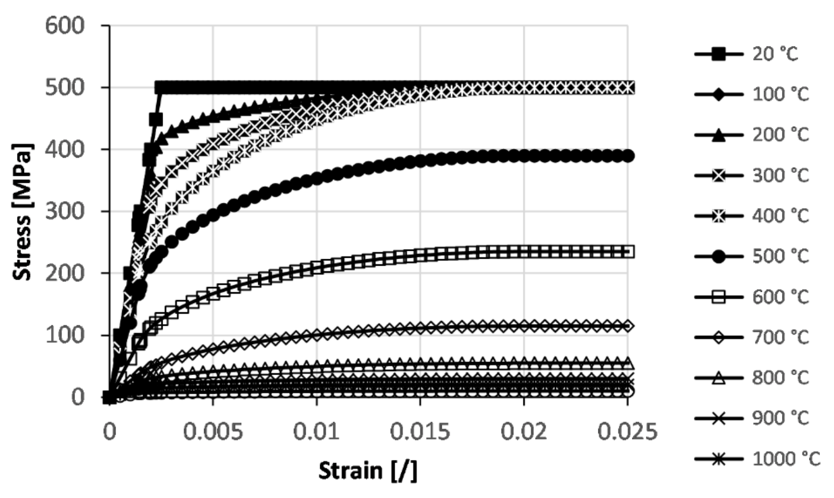
compression



tension

Co-funded by the Erasmus+ Programme of the European Union

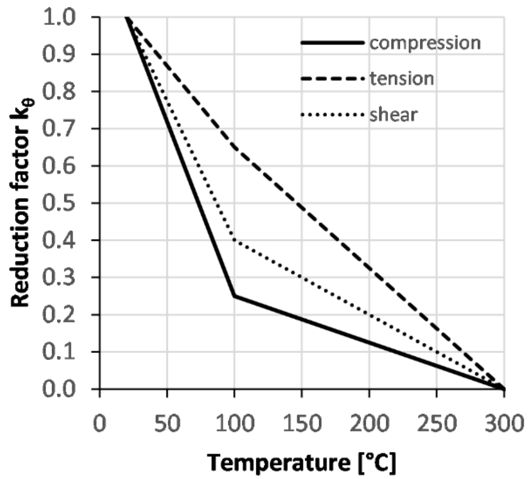
Stress-strain relations - Steel



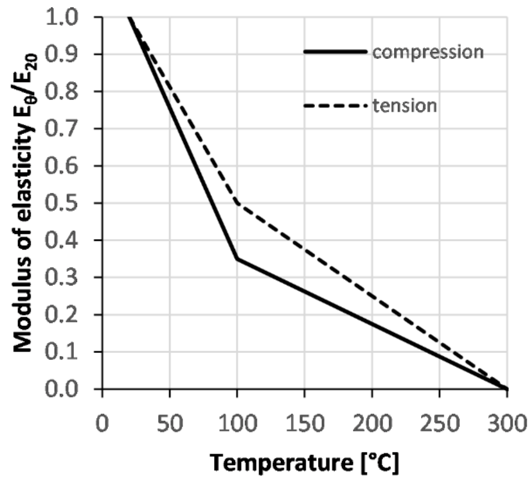
tension and compression

Co-funded by the Erasmus+ Programme of the European Union

Strength and stiffness reduction factors - Wood



strength

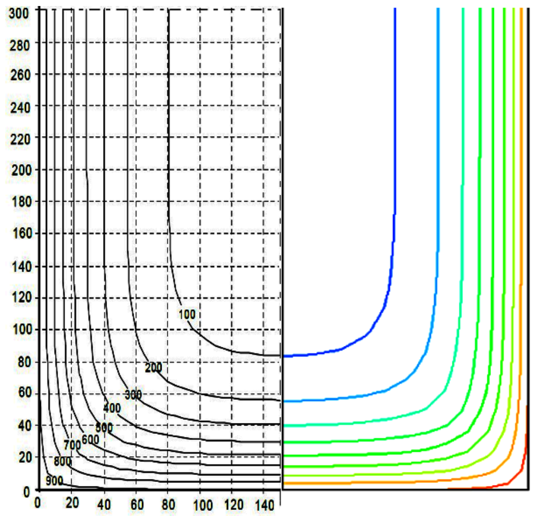


stiffness

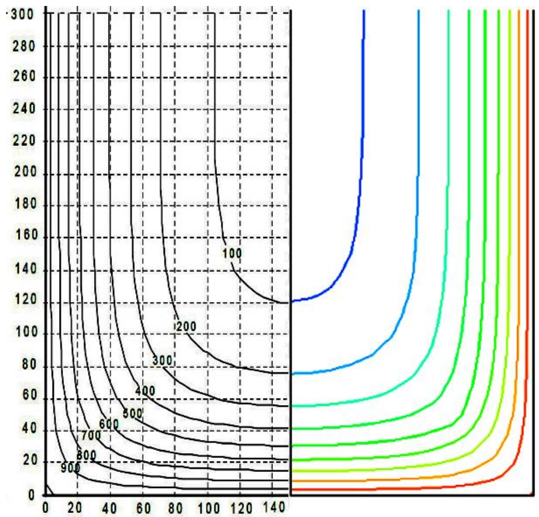
Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire response

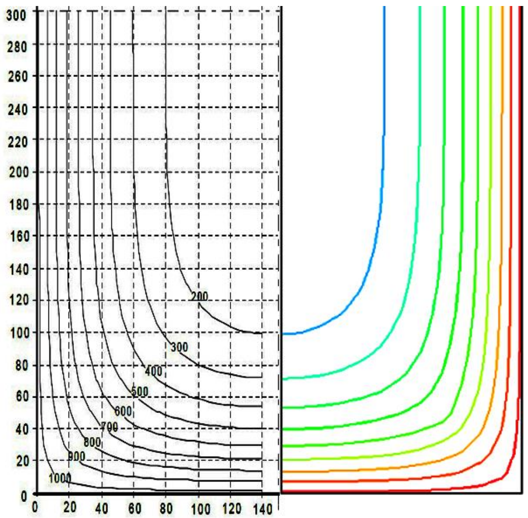
Verification and validation of the model



R60



R90

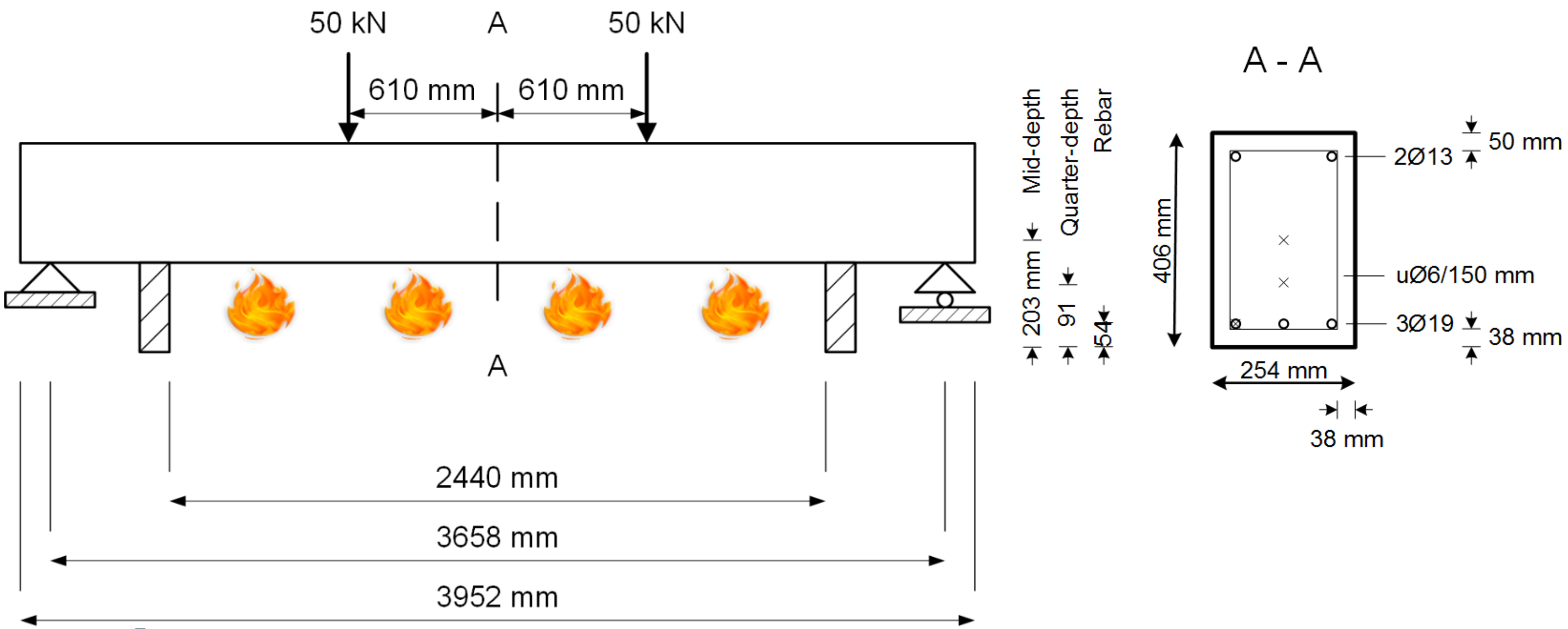


R120

Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire response

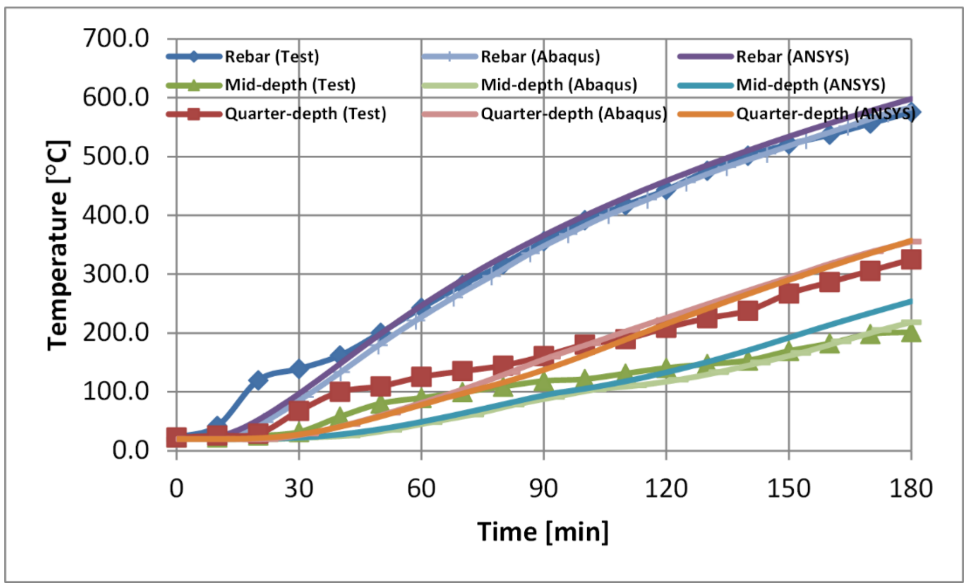
Fire test performed by Dwaikat and Kodur (2009)
Numerical model in ABAQUS by Kodur and Agrawal (2016)

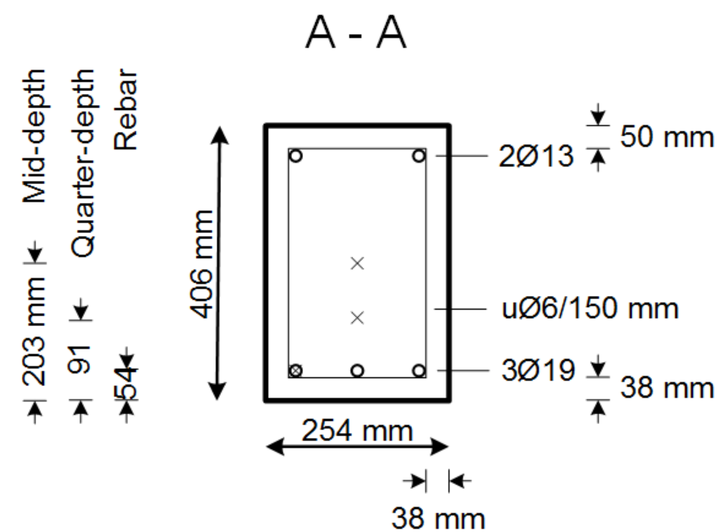


Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire response

Fire test performed by Dwaikat and Kodur (2009)
Numerical model in ABAQUS by Kodur and Agrawal (2016)

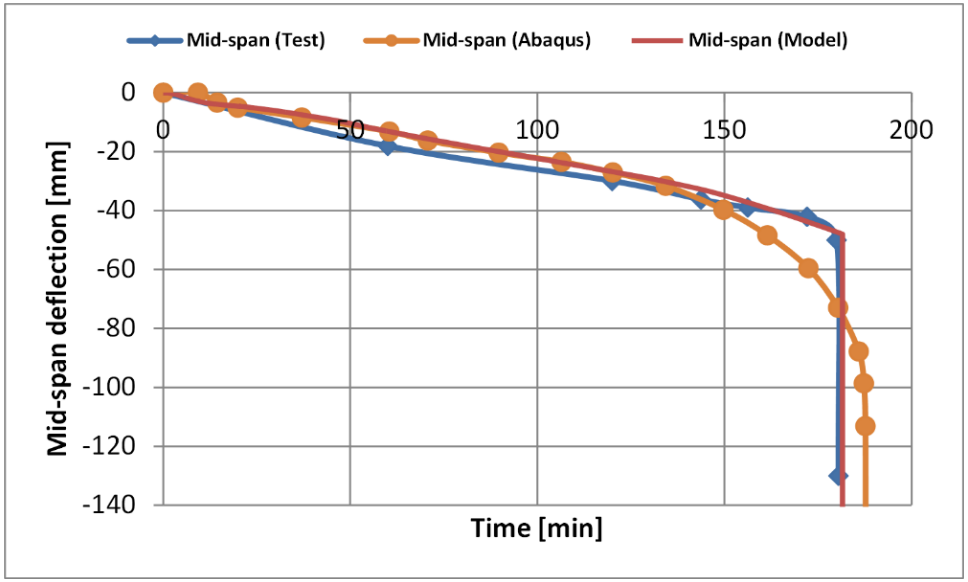


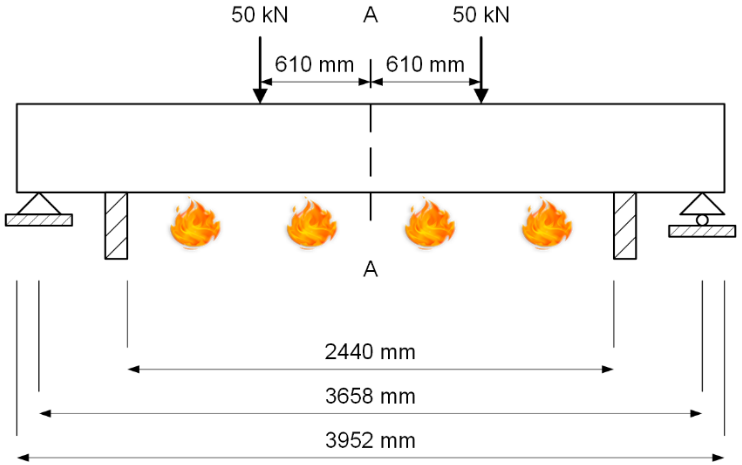


Co-funded by the
Erasmus+ Programme
of the European Union

Structural fire response

Fire test performed by Dwaikat and Kodur (2009)
Numerical model in ABAQUS by Kodur and Agrawal (2016)





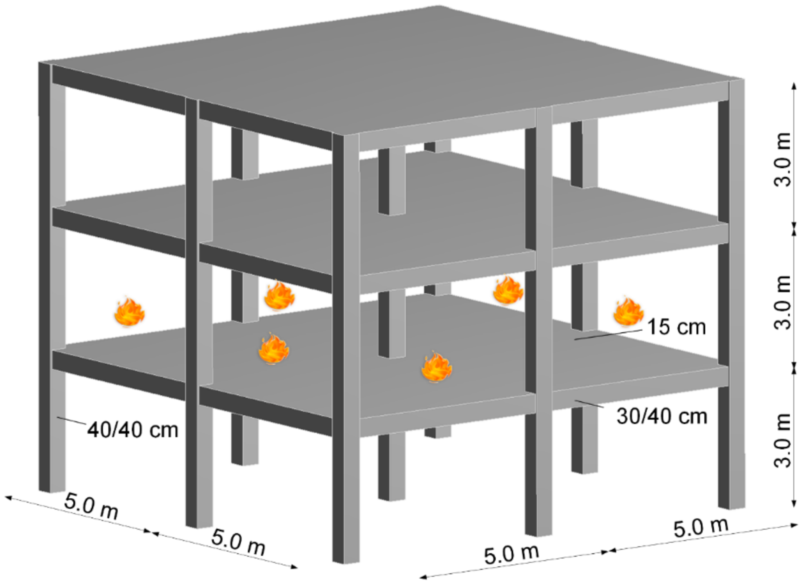
Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

Designed according to EN 1998-1-1 DCM 0.2g PGA

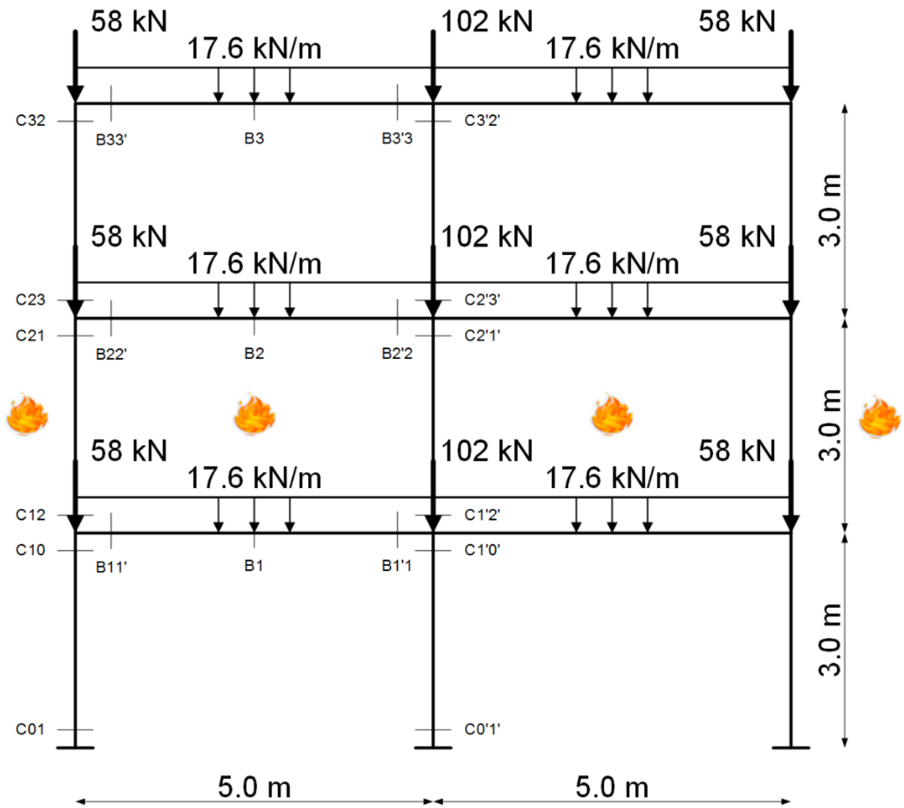
- EN 1992-1-1
- EN 1998-1-1

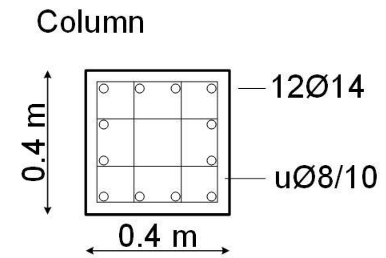
- C 30/37
- S 500 C

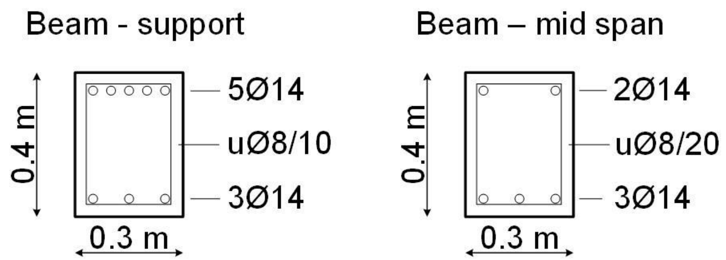


Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure







Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

Fire scenario
- 1^{st}, 2^{nd}, 3^{rd} storey

Aggregate type
- siliceous, calcareous

Initial load level
- 50%, 80% of Q

ISO 834

No.	Fire scenario	Load	Aggregate	Mark
1	1^{st} storey	50% „p“	Siliceous	P1O5S
2			Calcareous	P1O5C
3		80% „p“	Calcareous	P1O8C
4	2^{nd} storey	50% „p“	Siliceous	P2O5S
5			Calcareous	P2O5C
6		80% „p“	Calcareous	P2O8C
7	3^{rd} storey	50% „p“	Siliceous	P3O5S
8			Calcareous	P3O5C
9		80% „p“	Calcareous	P3O8C

Co-funded by the Erasmus+ Programme of the European Union

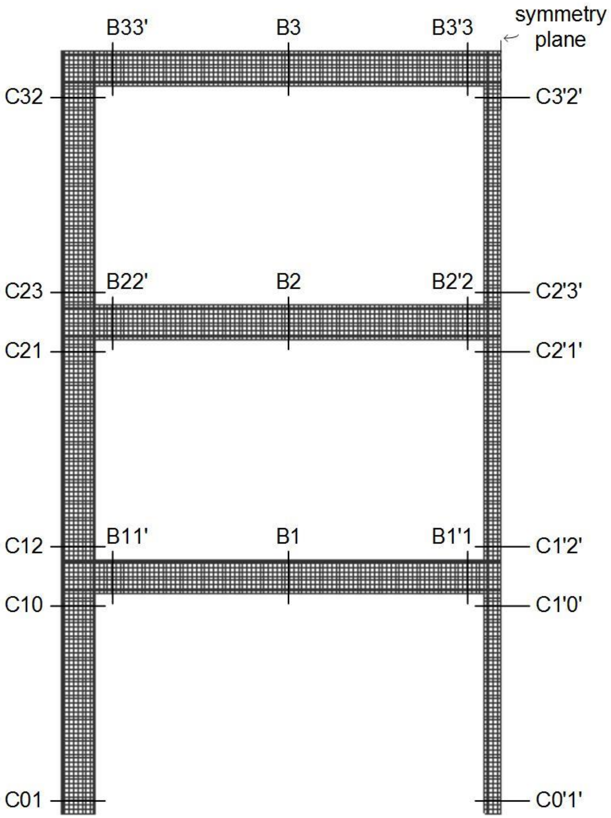
RC frame structure

Thermal response

- Thermal profiles - cross-sections
- Thermal profiles - reinforcement

Structural response

- Displacements
- Axial forces / bending moments
- Stresses
- Elastic, plastic, total mechanical and thermal strains in reinforcement bars

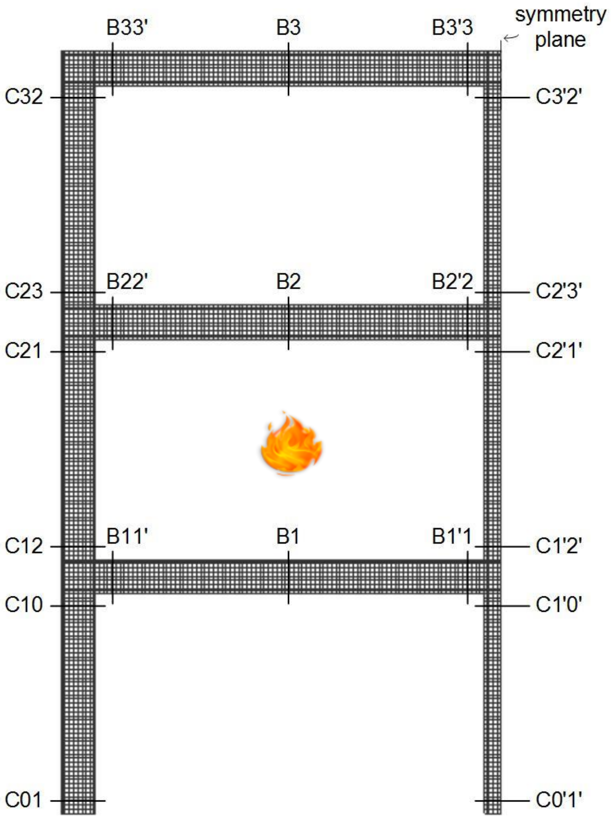


Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S

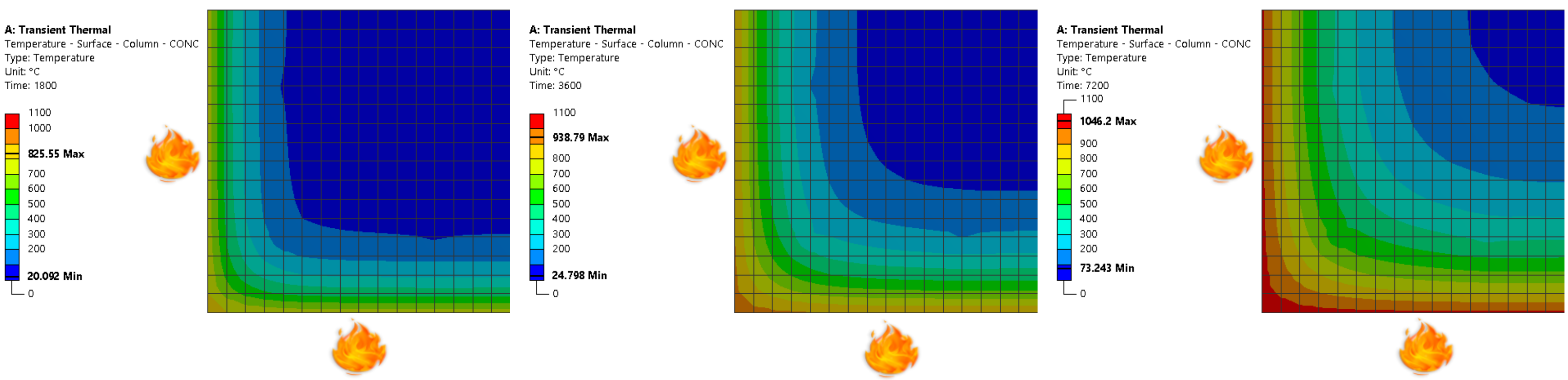
- Fire on 2nd storey
- 50% of variable load
- Siliceous aggregate



Co-funded by the Erasmus+ Programme of the European Union

RC frame structure

P2O5S - Thermal response - column (all surfaces exposed)



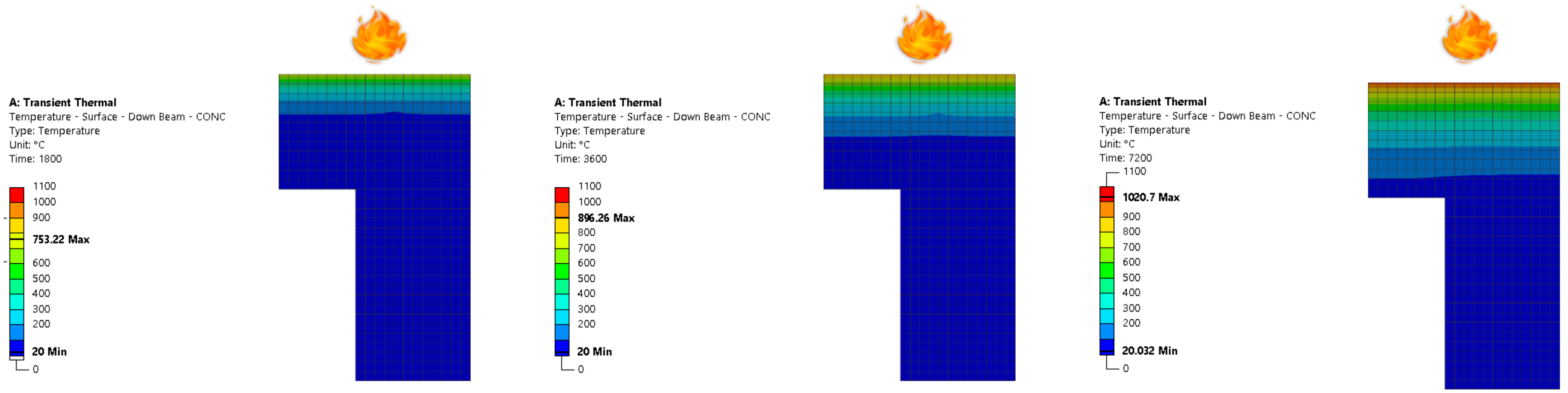
30 min 60 min 120 min

column 40/40 - 1/4 of the section

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Thermal response - beam (top exposed)



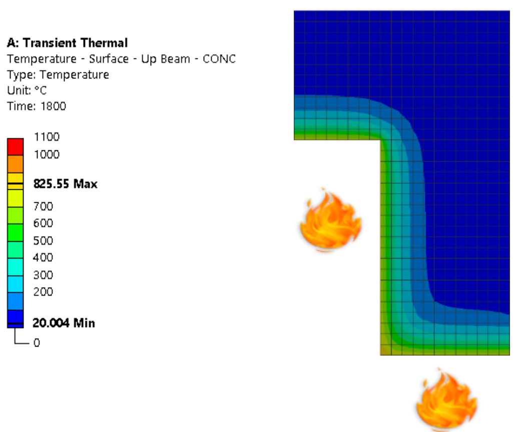
30 min | 60 min | 120 min

beam 30/40 - 1/2 of the section

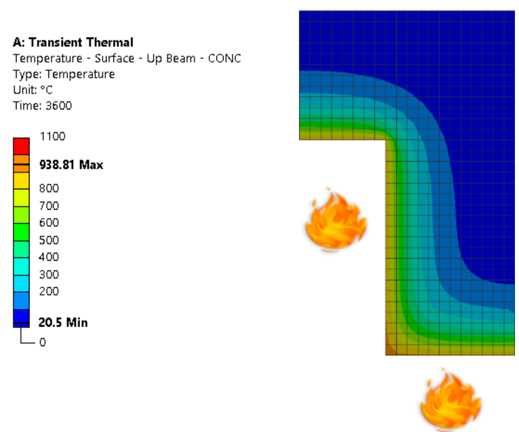
Co-funded by the Erasmus+ Programme of the European Union

RC frame structure

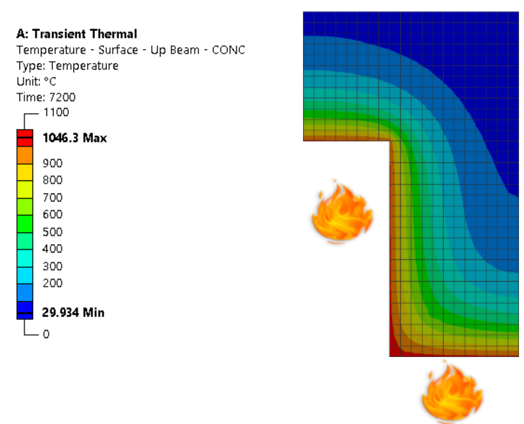
P2O5S - Thermal response - beam (bottom/side exposed)



30 min



60 min



120 min

beam 30/40 - 1/2 of the section

Co-funded by the
Erasmus+ Programme
of the European Union

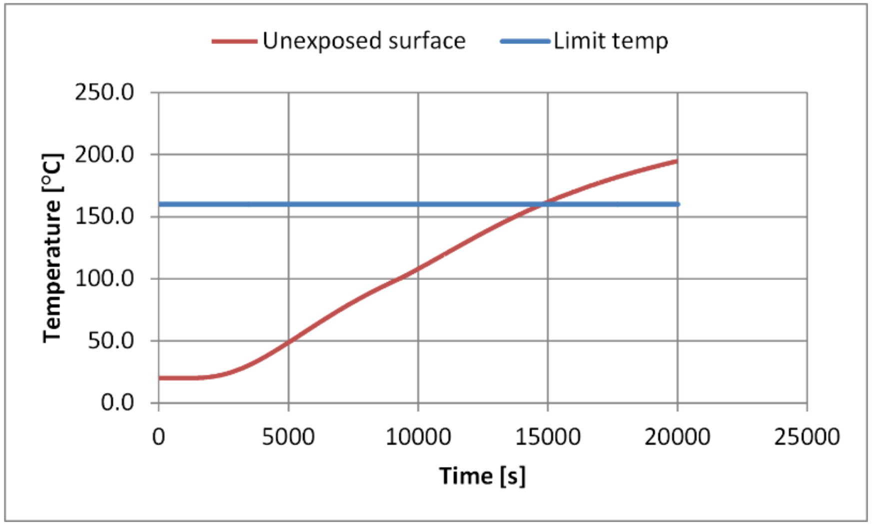
RC frame structure

P2O5S - Insulation criteria (I)

RC slab - compartment boundary

- average temperature rise on unexposed surface < 140°C
- maximum temperature rise on unexposed surface < 180°C

RC slab d = 15 cm → I 240



Co-funded by the Erasmus+ Programme of the European Union

RC frame structure

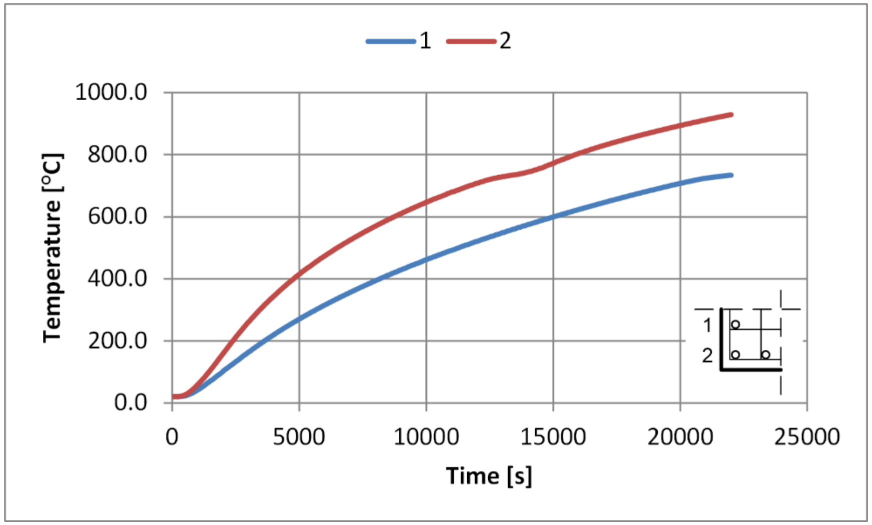
P2O5S - Thermal response of reinforcement

60 min

- concrete max temp. 940°C
  reinforcement max temp. 310°C

120 min

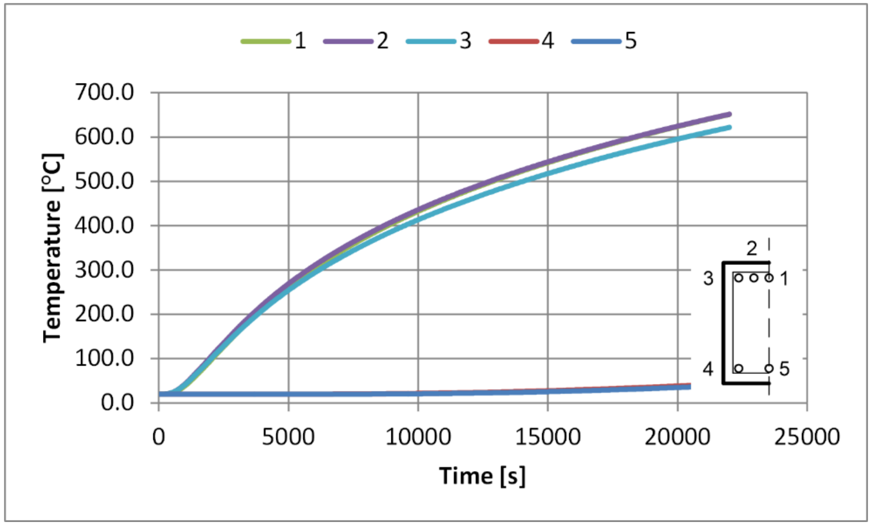
- concrete max temp. 1050°C
  reinforcement max temp. 540°C



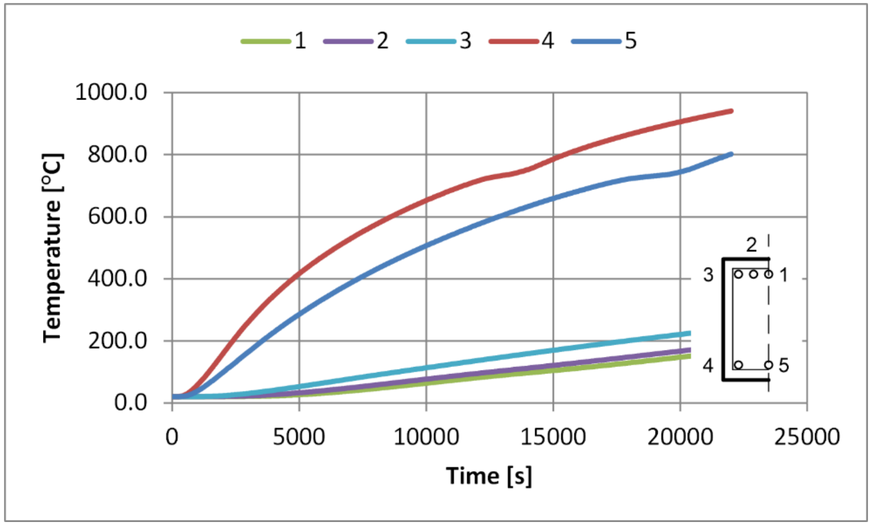
column (all surfaces exposed)

RC frame structure

P2O5S - Thermal response of reinforcement



beam (top exposed)

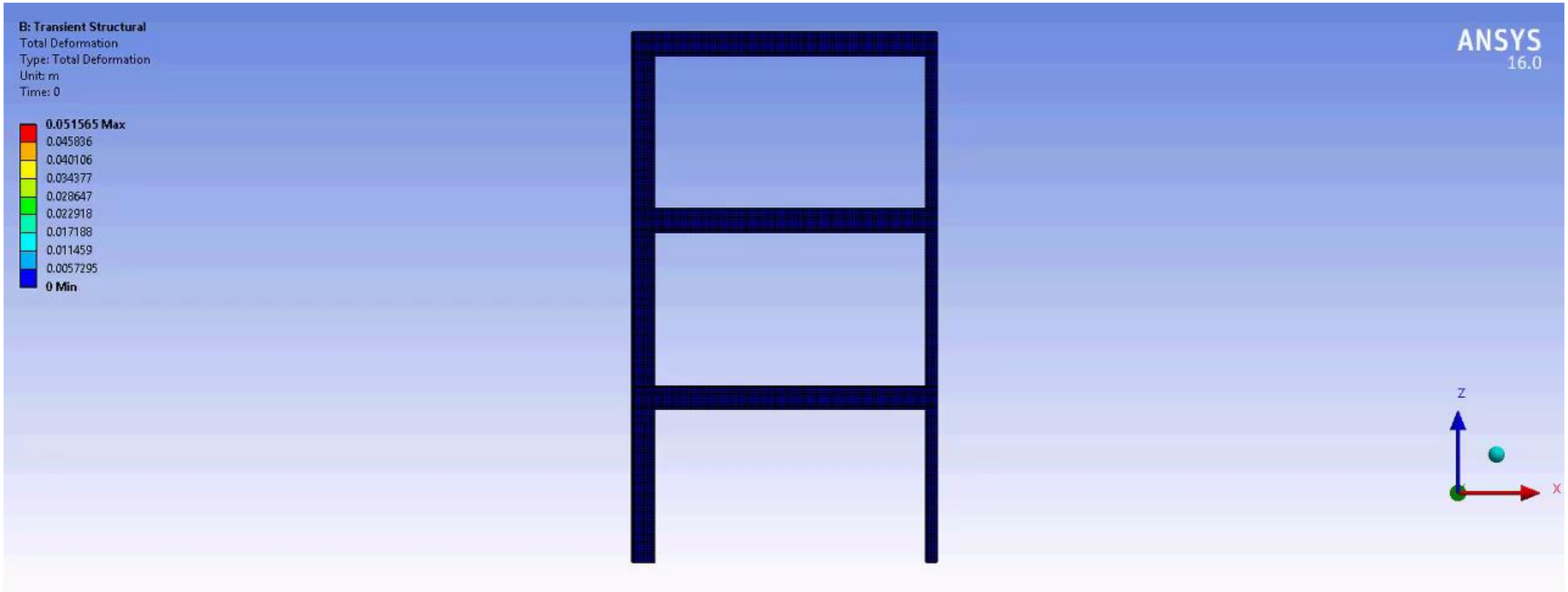


beam (bottom/side exposed)

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

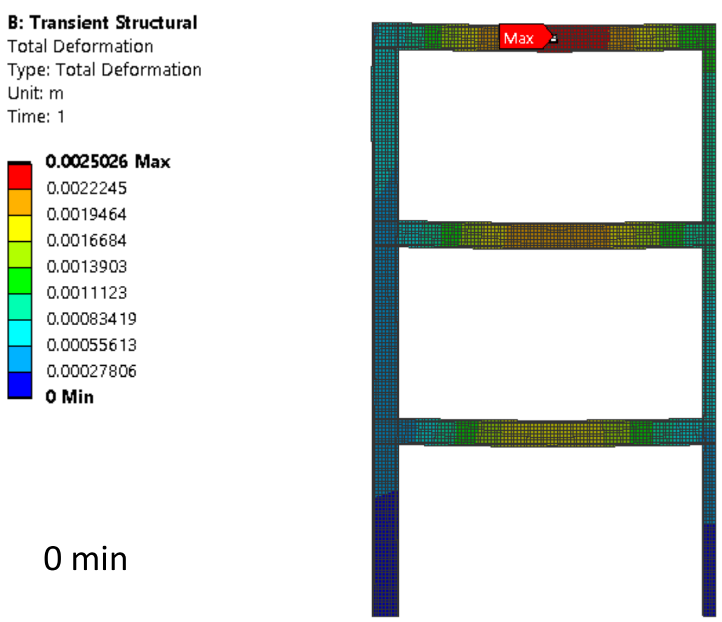
P2O5S - Structural response - Total displacements



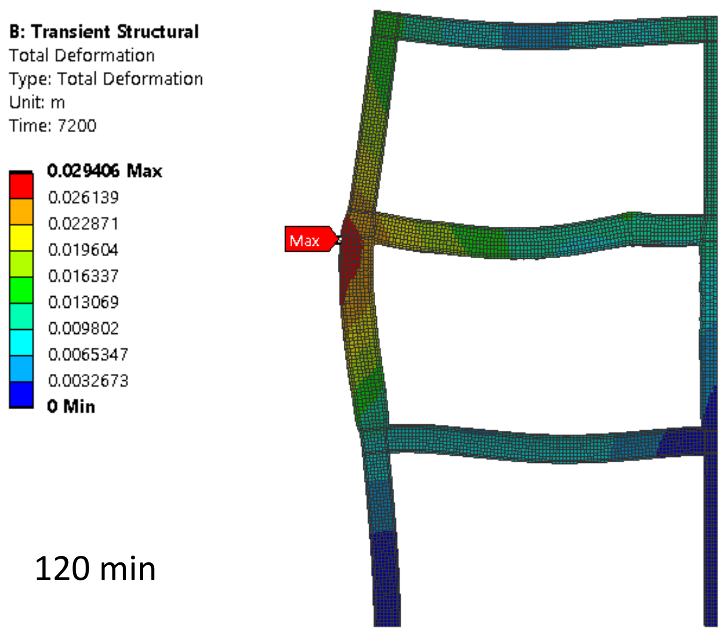
Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Structural response - Total displacements



0 min

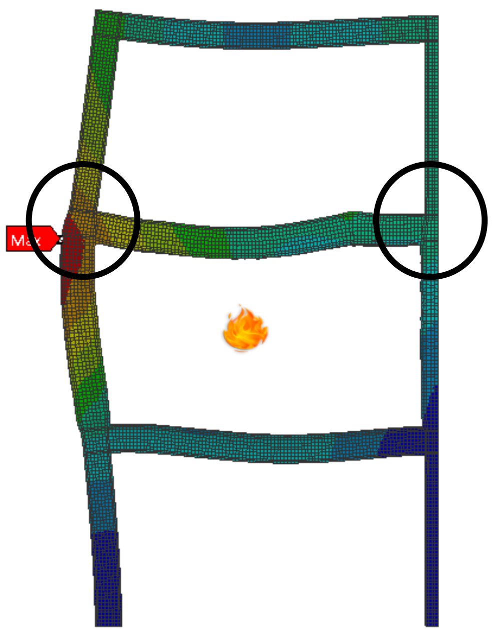


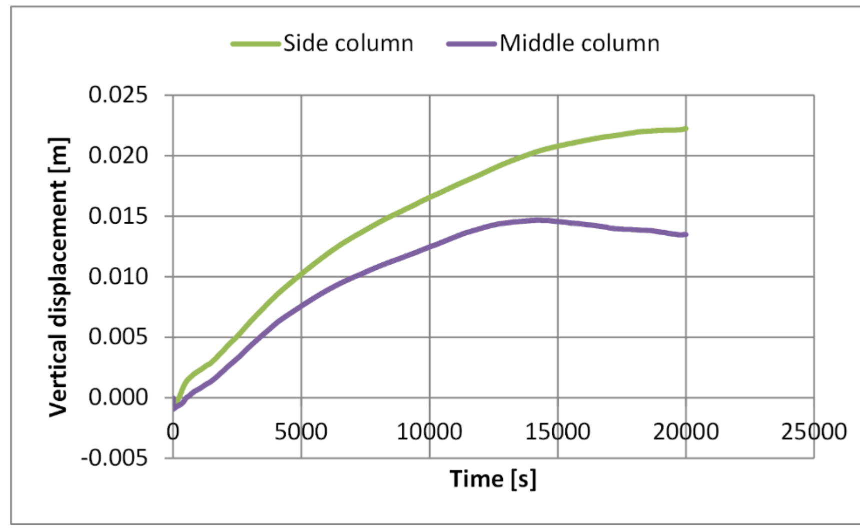
120 min

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Structural response - Vertical displacements



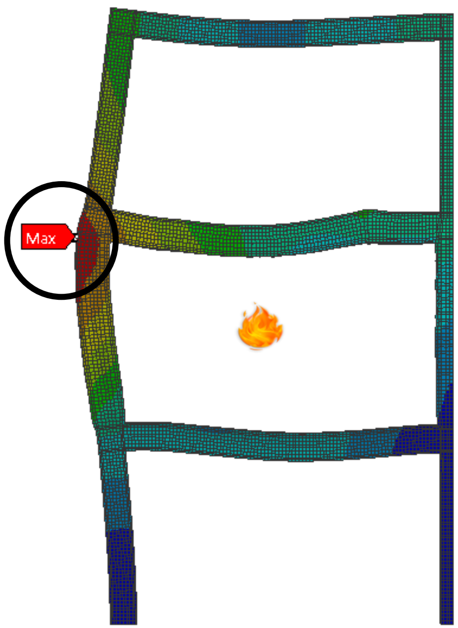


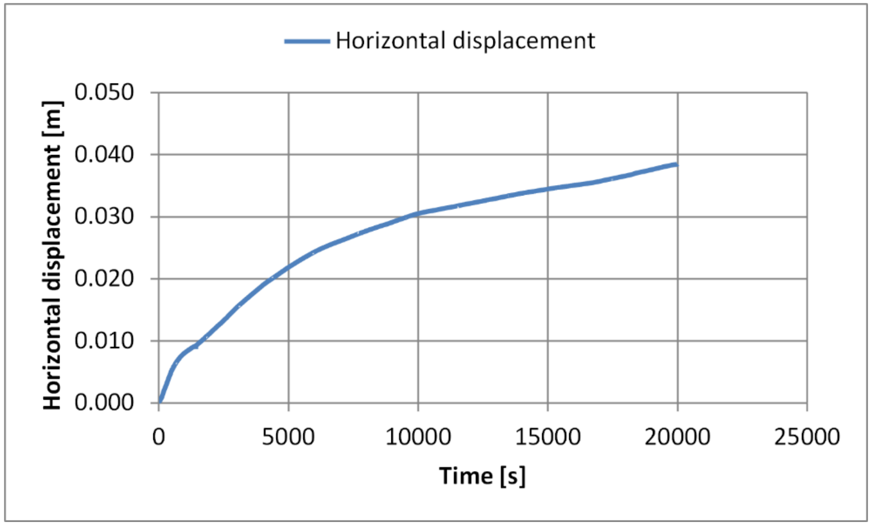
exposed column top
vertical displacement

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Structural response - Horizontal displacements



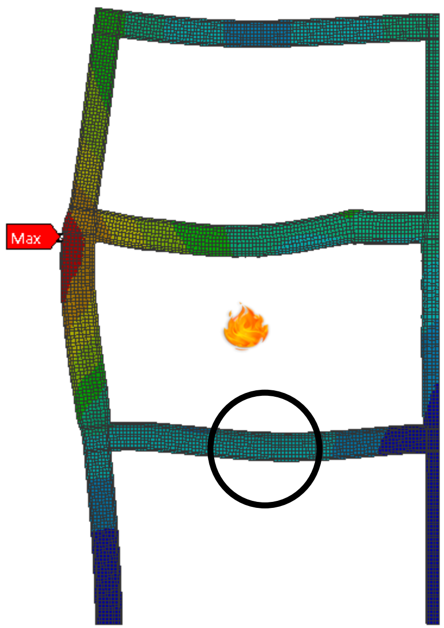


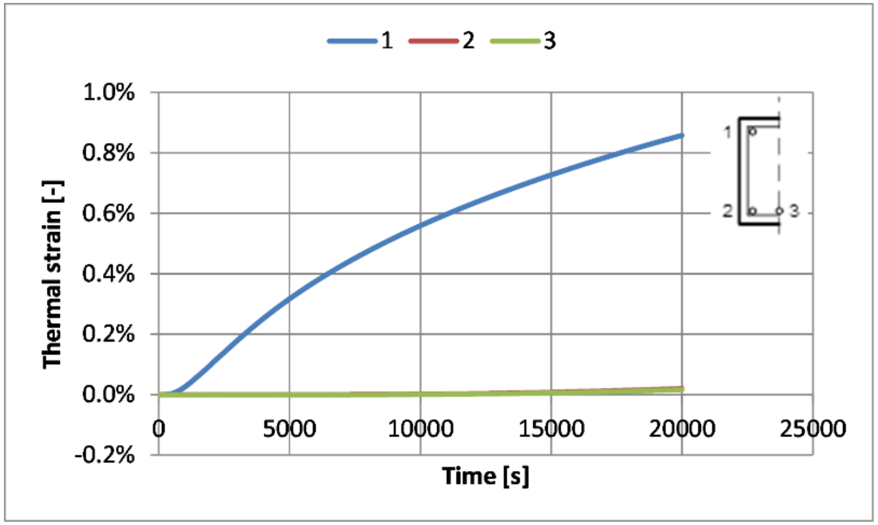
max horizontal displacement

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Structural response - Reinforcement



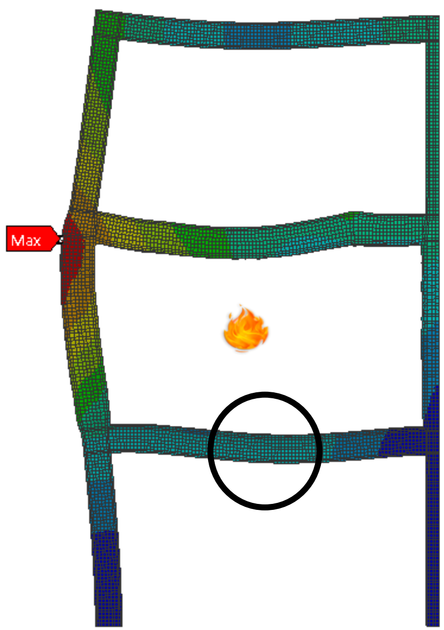


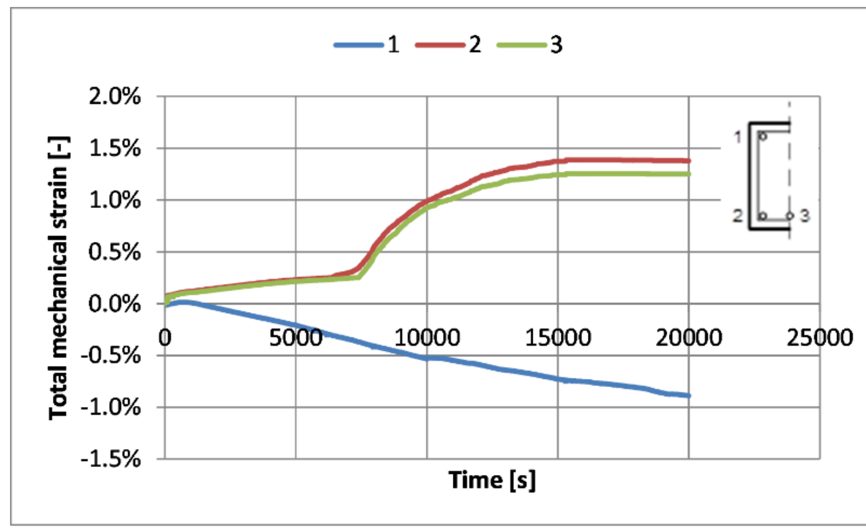
thermal strain in reinforcement
bars at beam B1 mid-span

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Structural response - Reinforcement



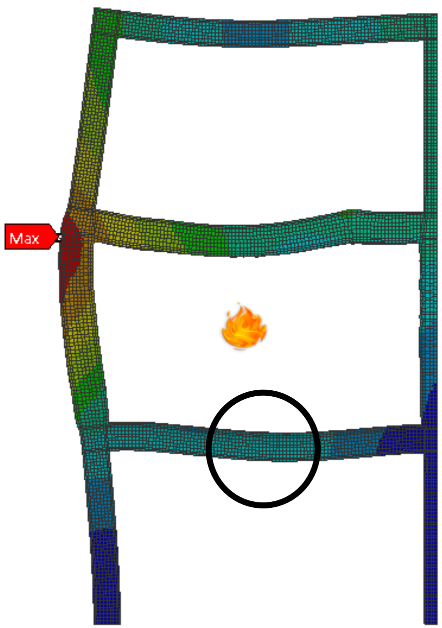


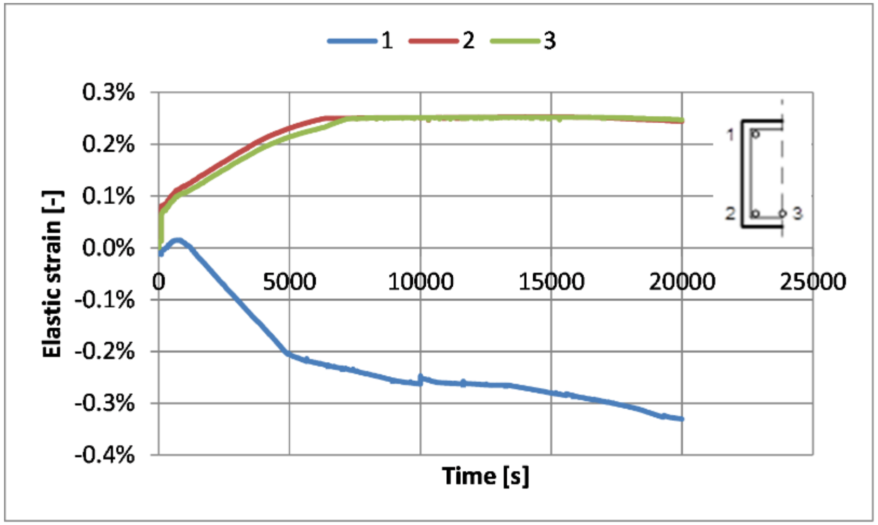
mechanical strain in reinforcement bars at beam B1 mid-span

Co-funded by the Erasmus+ Programme of the European Union

RC frame structure

P2O5S - Structural response - Reinforcement



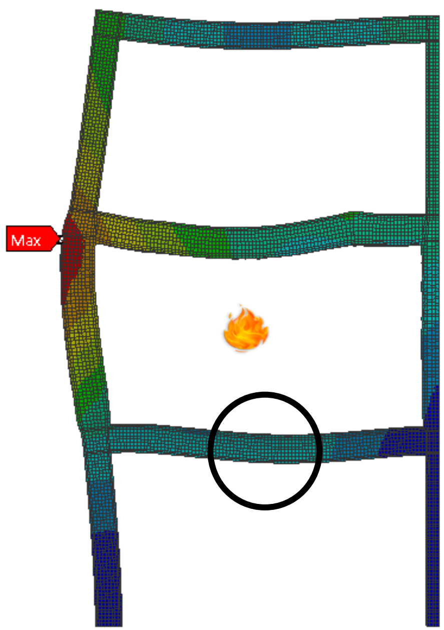


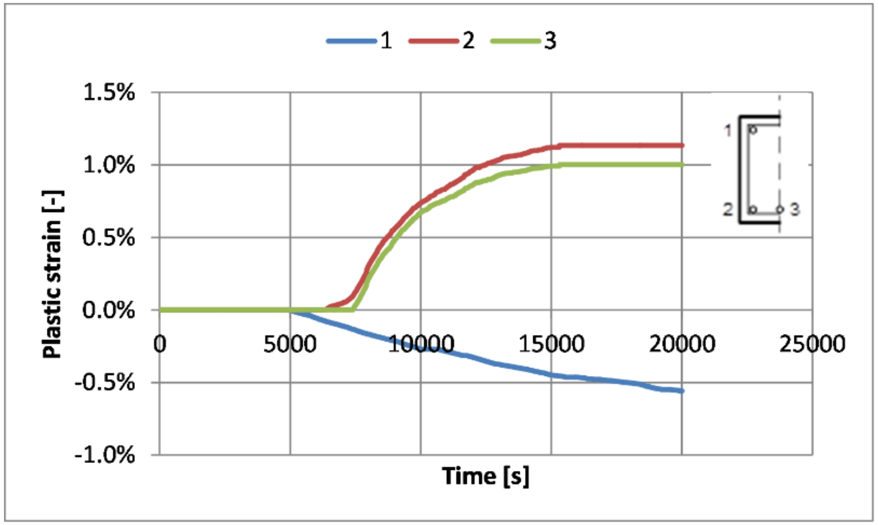
elastic strain in reinforcement bars
at beam B1 mid-span

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Structural response - Reinforcement



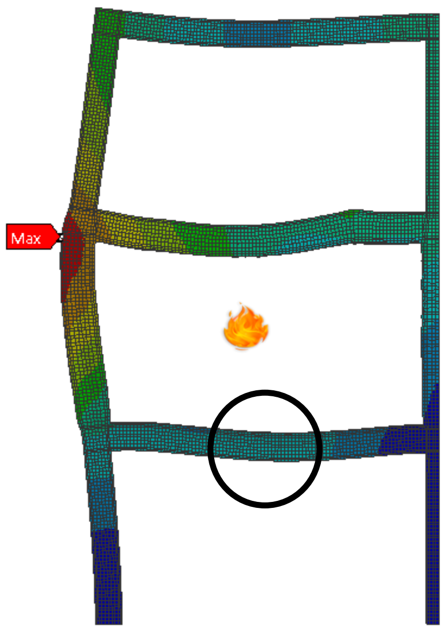


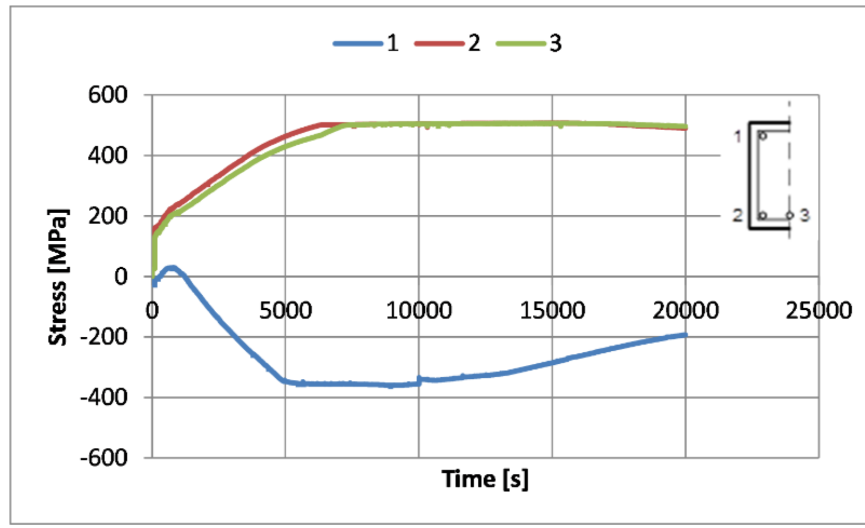
plastic strain in reinforcement bars
at beam B1 mid-span

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Structural response - Reinforcement



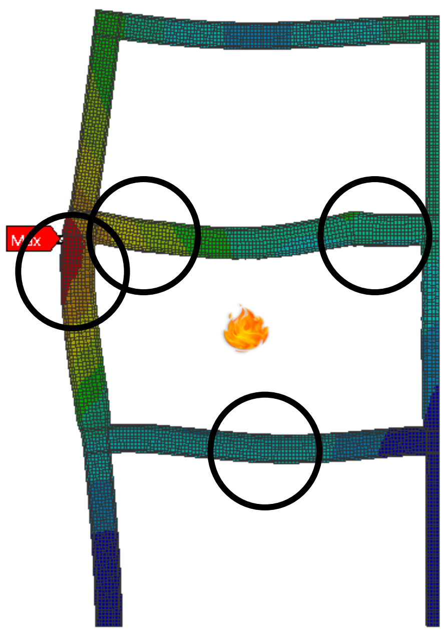


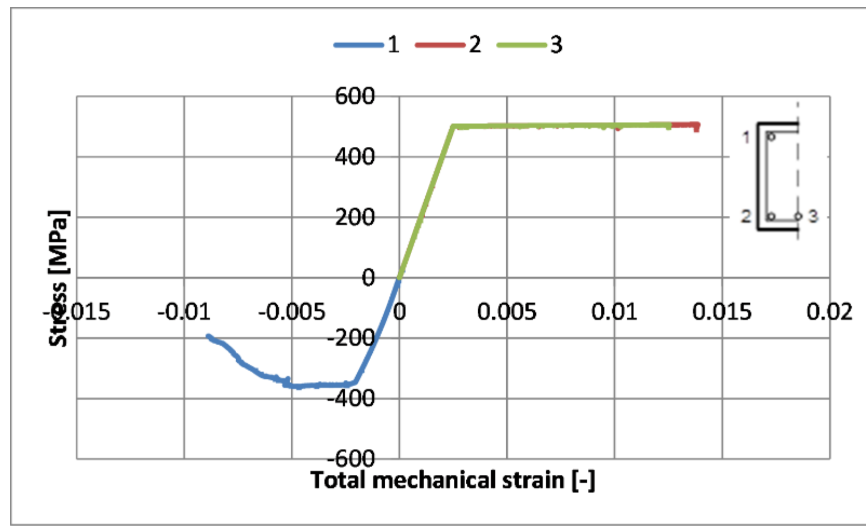
stress in reinforcement bars
at beam B1 mid-span

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

P2O5S - Structural response - Reinforcement



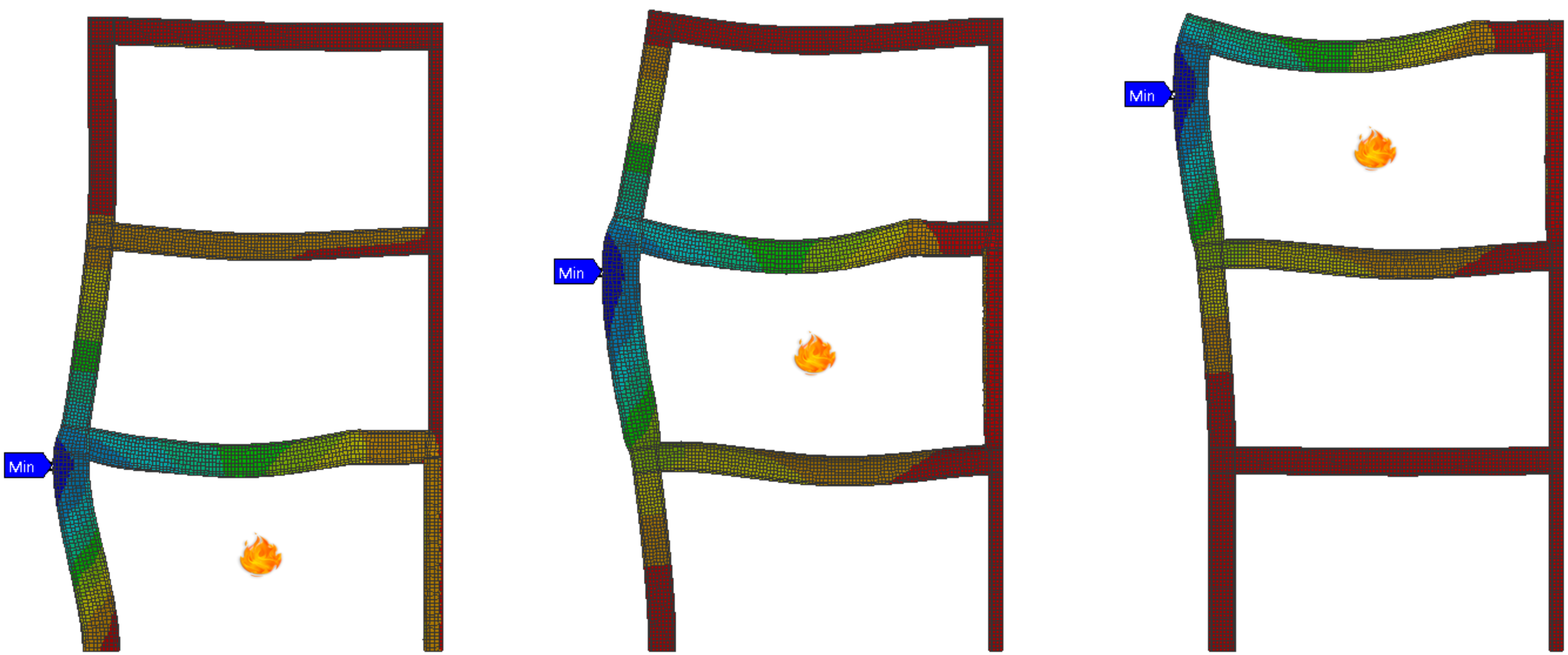


stress/strain in reinforcement bars
at beam B1 mid-span

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

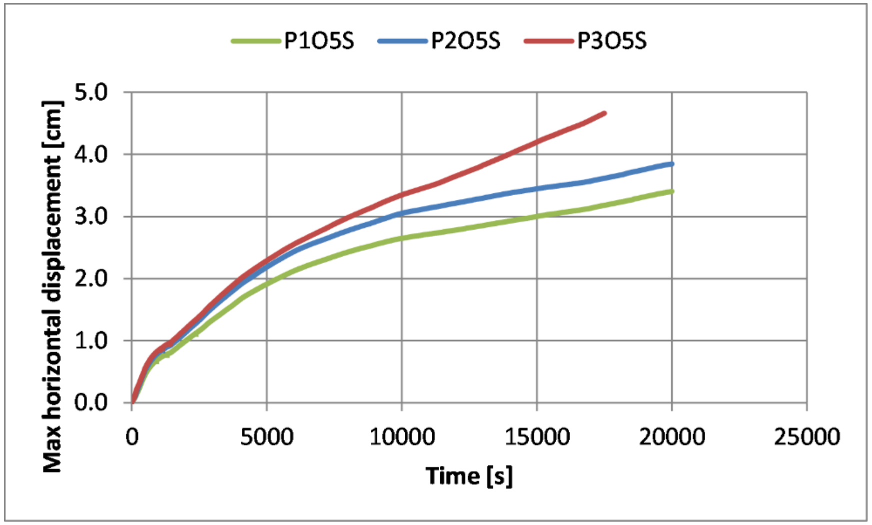
Parametric analysis - fire scenario



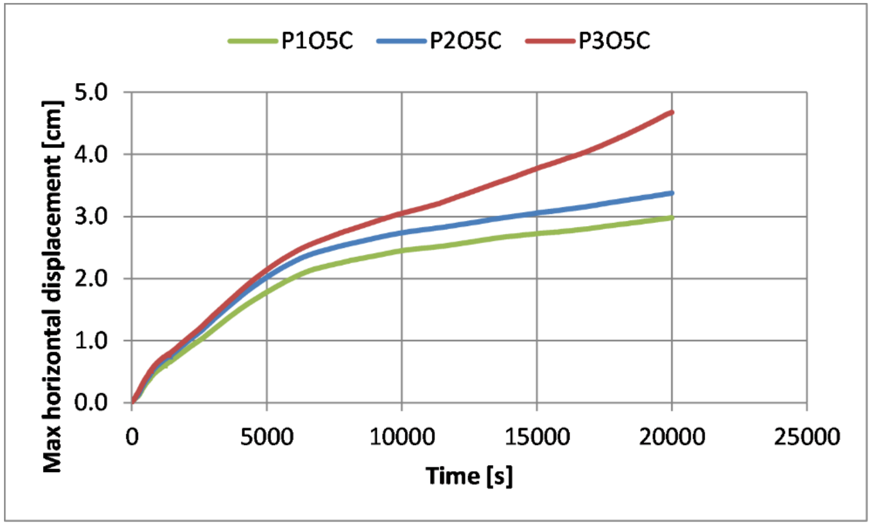
Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

Parametric analysis - fire scenario and aggregate type



max horizontal displacements
siliceous aggregate

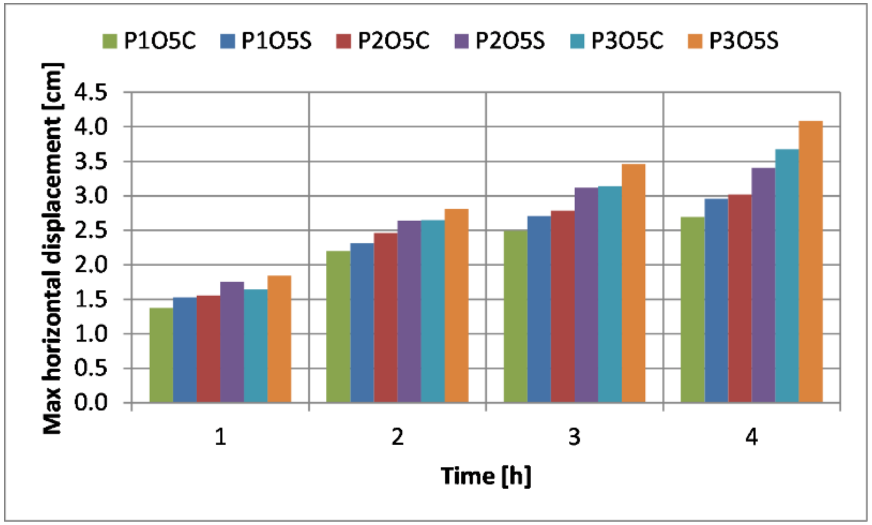


max horizontal displacements
calcareous aggregate

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

Parametric analysis - fire scenario and aggregate type

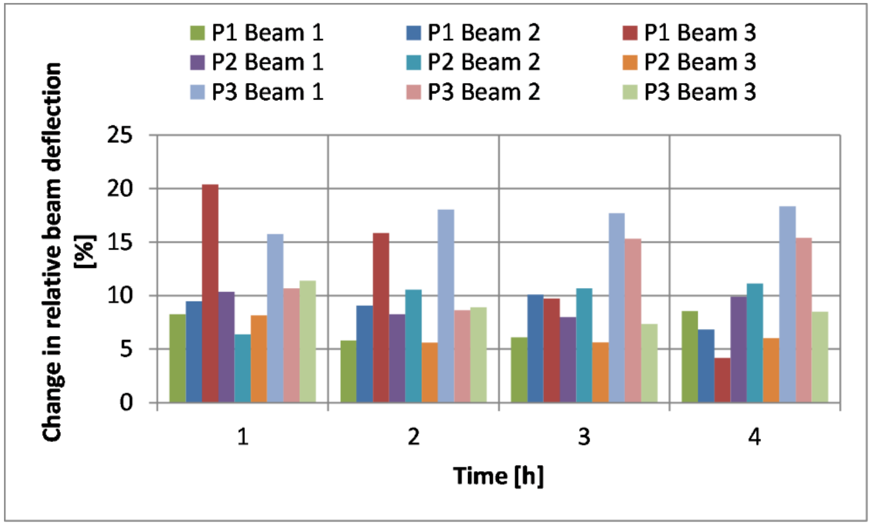


max horizontal displacements

Co-funded by the
Erasmus+ Programme
of the European Union

RC frame structure

Parametric analysis - fire scenario and variable load



change in relative beam deflections

Co-funded by the Erasmus+ Programme of the European Union

Conclusions

- Fire is an accidental action
- If not supressed, fire can initiate nonlinear inelastic structural response
- Structures need to be designed and constructed to be able to sustain certain fire resistance time
- Fire resistance can be determined by tests or by calculation methods, the latter utilizing mainly numerical methods, such as the finite element method
- Properly developed numerical models are able to assess realistic behaviour of structures exposed to fire
- RC frame structure designed according to Eurocode standards for seismically active regions has proved to be very resistant in case of fire, due to the inherent load bearing and deformation capacity reserve

Co-funded by the
Erasmus+ Programme
of the European Union

K-FORCE

Co-funded by the Erasmus+ Programme of the European Union

Thank you
for your attention

idzolev@uns.ac.rs

Knowledge **FO**r **R**esilient so**C**i**E**ty