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SPECIAL MOBILITY STRAND

FIRE SAFETY OF TIMBER STRUCTURES

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Introduction

Sustainability - main objectives of sustainable design:

- Reduce or completely avoid depletion of critical resources like energy, water and raw materials;
- prevent environmental degradation caused by facilities and infrastructure during their life cycle;
- create built environment which is liveable, comfortable and safe.

Timber is considered as renewable and sustainable construction material because:

- absorbs carbon dioxide while growing;
- it`s production is low energy and low impact process;
- it can be recycled or used as a bio fuel;
- the construction work is efficient and economical;
- it is characterized by durability and excellent thermal performance.

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Introduction

Traditional house - Timber frame structure

Modern timber buildings

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Introduction

Disadvantage of timber:

Combustible when exposed to high temperatures and fire!

Introduction

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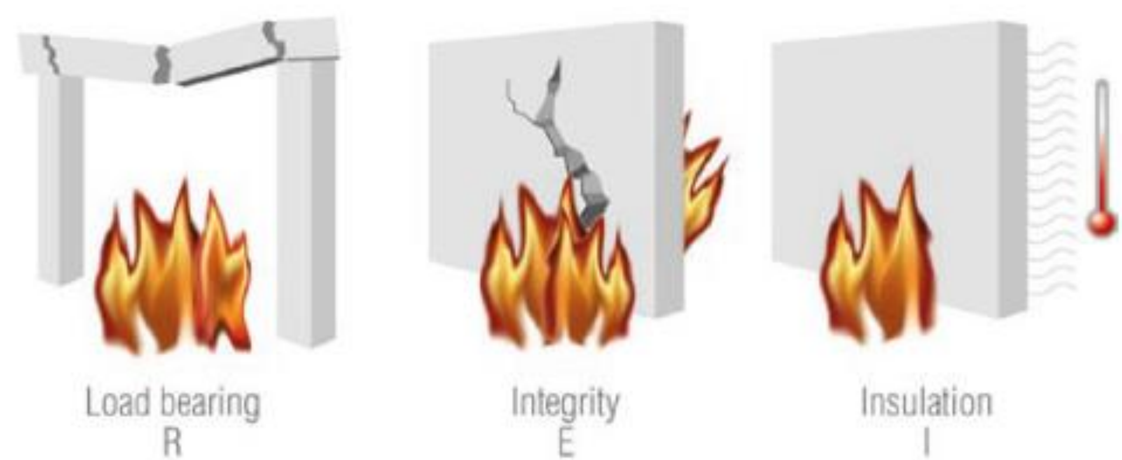
In order to prevent serious consequences, fire as an accidental action has to be taken under consideration in timber structural design.

Essential requirements:

- Load bearing resistance (R);
- Structural integrity (E);
- Insulation (I).



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Introduction

Fire resistance of an element, of a part, or of a whole structure is: ability to fulfil the previously mentioned requirements for a specified load level, for a specified fire exposure and for a specified period of time.

Ensuring the required fire resistance of a building structure, leads us a step closure to ensuring its fire safety.

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Introduction

Fire resistance of an element, of a part, or of a whole structure is: ability to fulfil the previously mentioned requirements for a specified load level, for a specified fire exposure and for a specified period of time.

By adequate design, the structure should withstand the burnout

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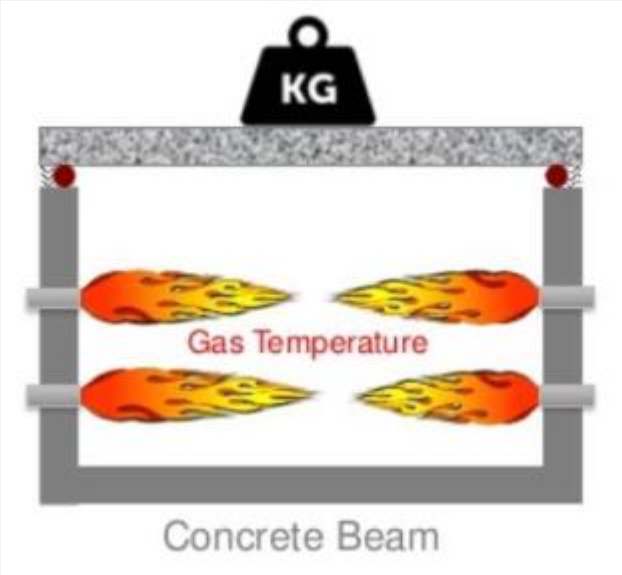
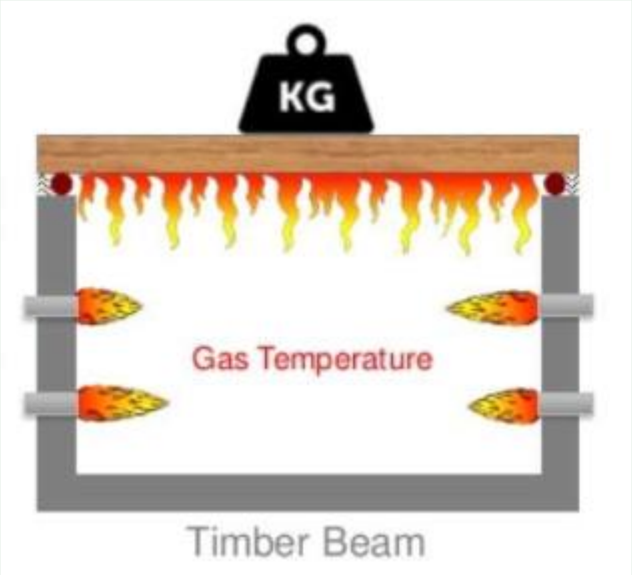
Introduction

Testing of timber elements:

Conventional furnaces were not intended for timber!





The test on concrete will use more fuel than test on timber to yield the same gas temperature in the furnace.

Do the timber buildings have less fuel in them than concrete buildings ?

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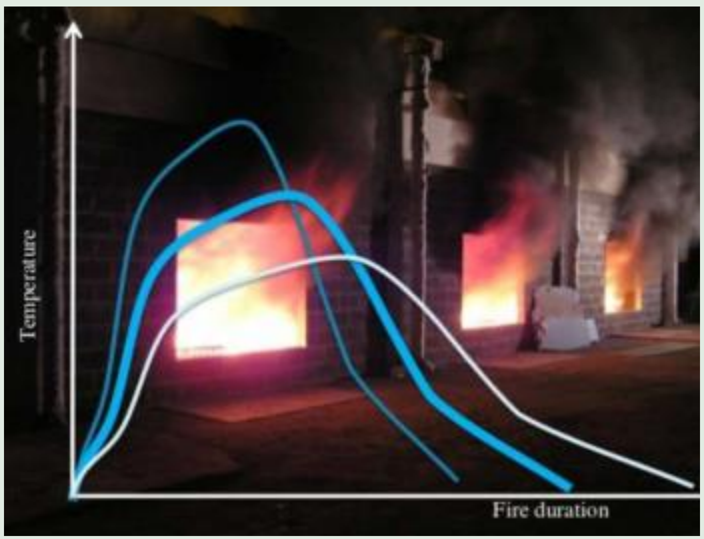
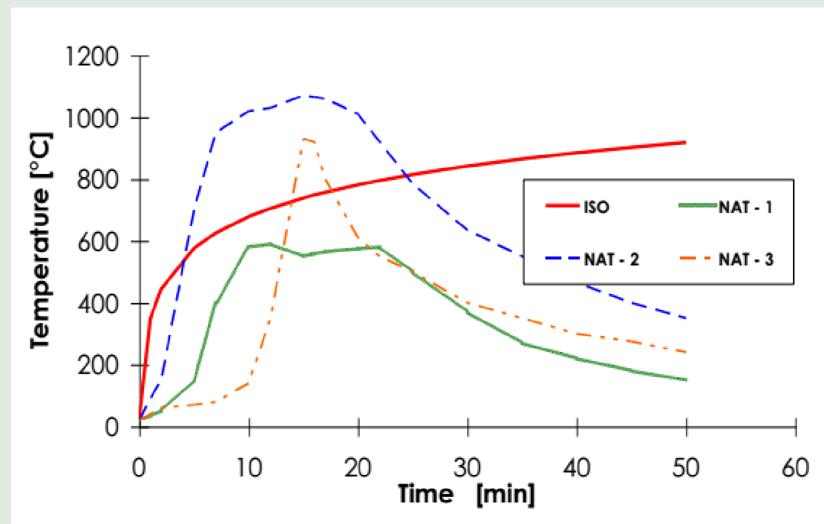
Total fire engineering design

Develop the design fire(s)

Non-combustible construction:





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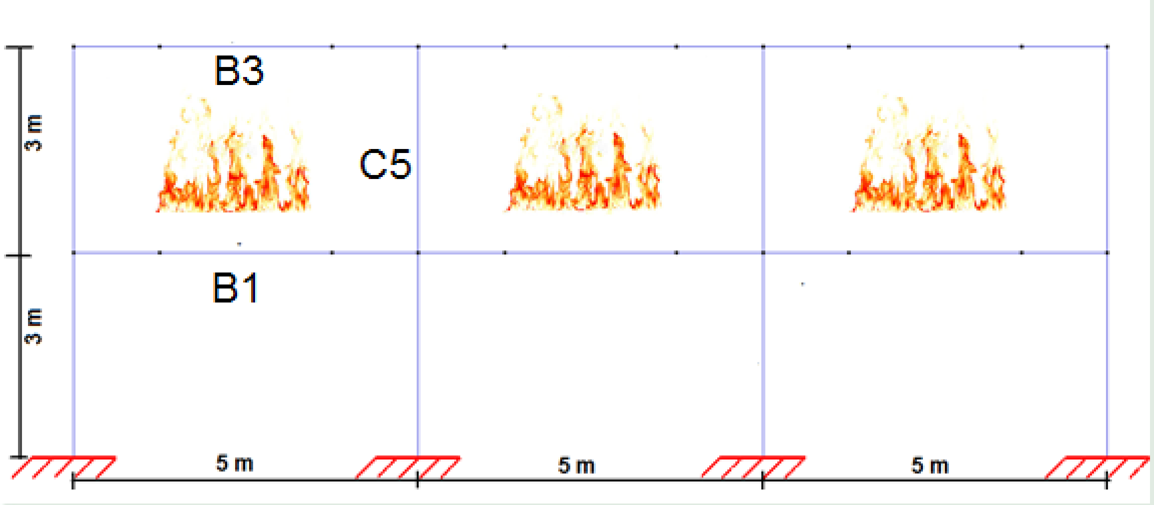
Total fire engineering design

Non-combustible construction:



Develop the design fire(s)

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Fire analysis: Thermal exposure

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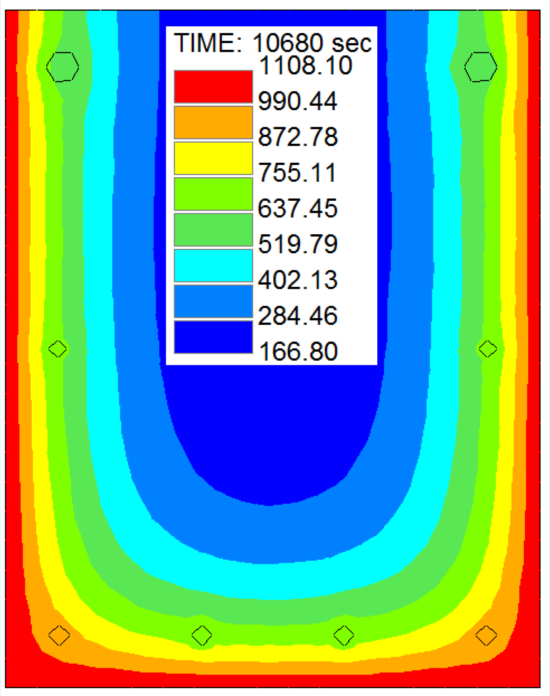
Total fire engineering design

Non-combustible construction:



Develop the design fire(s)

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Fire analysis: Thermal exposure

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Structural heat transfer analysis

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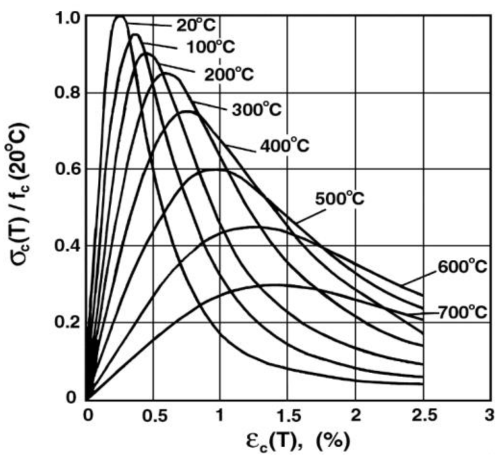
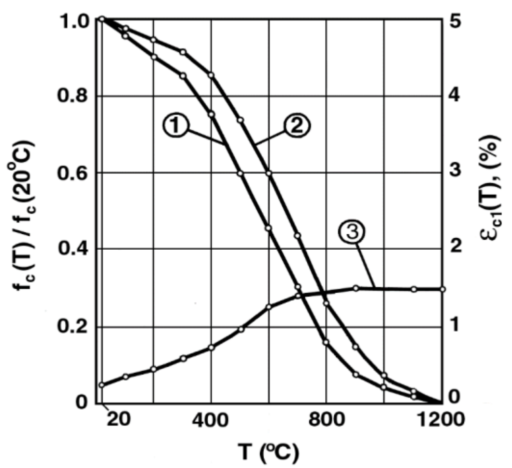
Total fire engineering design

Non-combustible construction:





concrete

Develop the design fire(s)

Fire analysis: Thermal exposure

Structural heat transfer analysis

Material response at high temperatures

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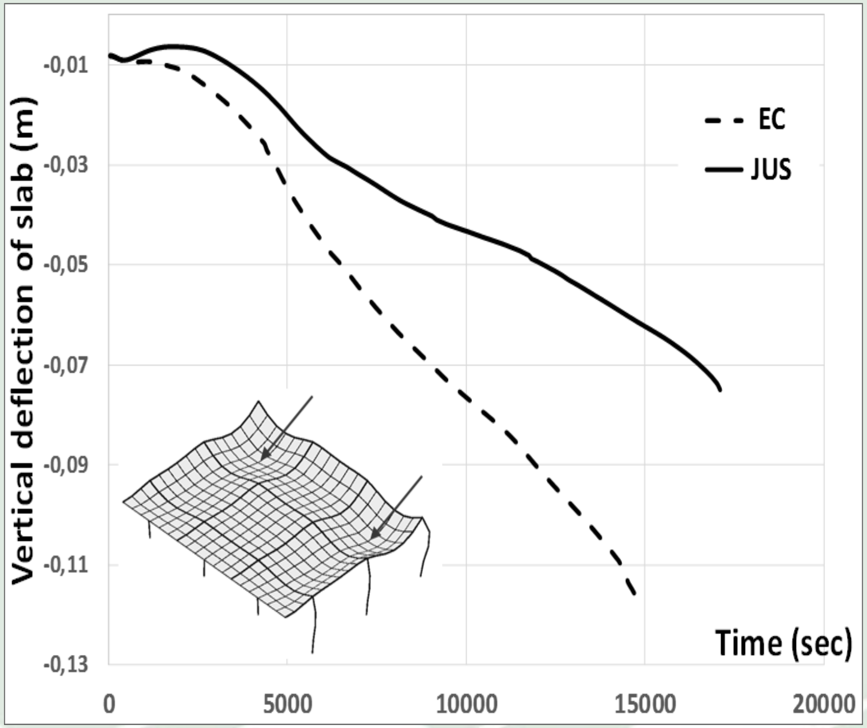
Total fire engineering design

Non-combustible construction:



Develop the design fire(s)

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Fire analysis: Thermal exposure

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Structural heat transfer analysis

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Material response at high temperatures

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Structural response at high temperatures

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Total fire engineering design

Develop the design fire(s)

Combustible construction:

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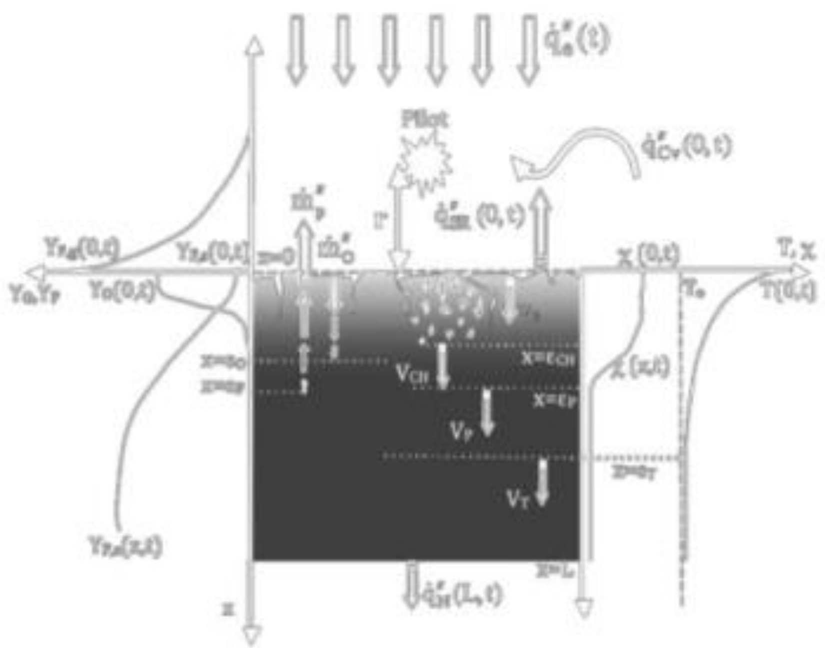
Total fire engineering design

Combustible construction:



Timber heat transfer model

Develop the design fire(s)

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Thermal exposure and heat transfer

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Total fire engineering design

Combustible construction:

Material tests of engineered timber under radiative heat flux

Develop the design fire(s)

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Thermal exposure and heat transfer

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Material response at high temperatures

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Total fire engineering design

Combustible construction:

Develop the design fire(s)

Thermal exposure and heat transfer

Material response at high temperatures

Structural response at high temperatures

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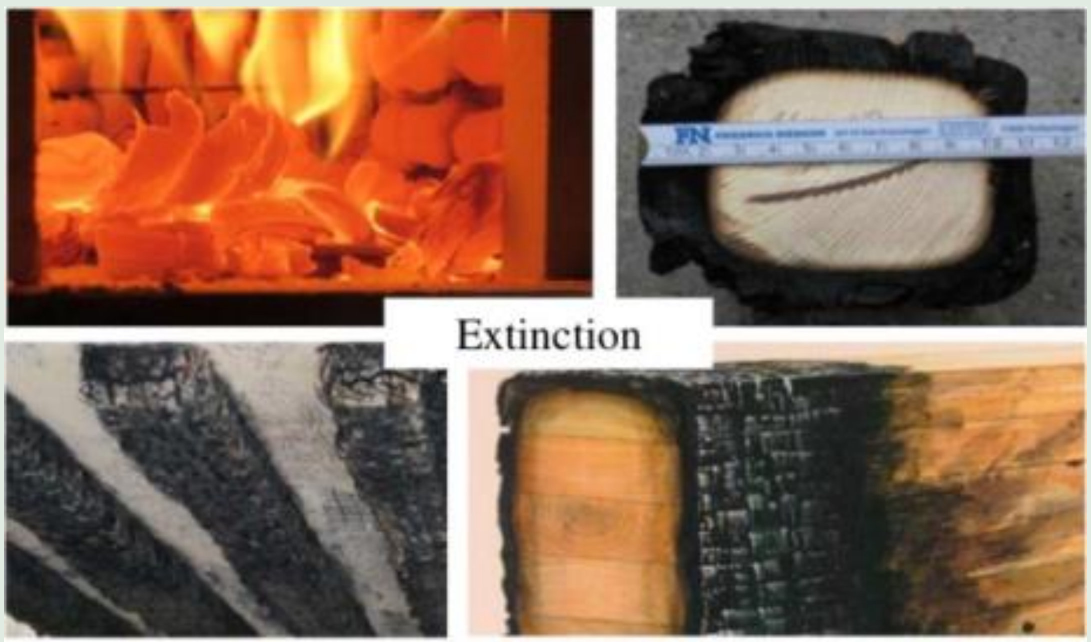
Total fire engineering design

Combustible construction:



Design needs to satisfy *both stability and burnout* *performance criteria*

- **Develop the design fire(s)**
- **Thermal exposure and heat transfer**
- **Material response at high temperatures**
- **Structural response at high temperatures**
- **Does the structure survive burnout?**

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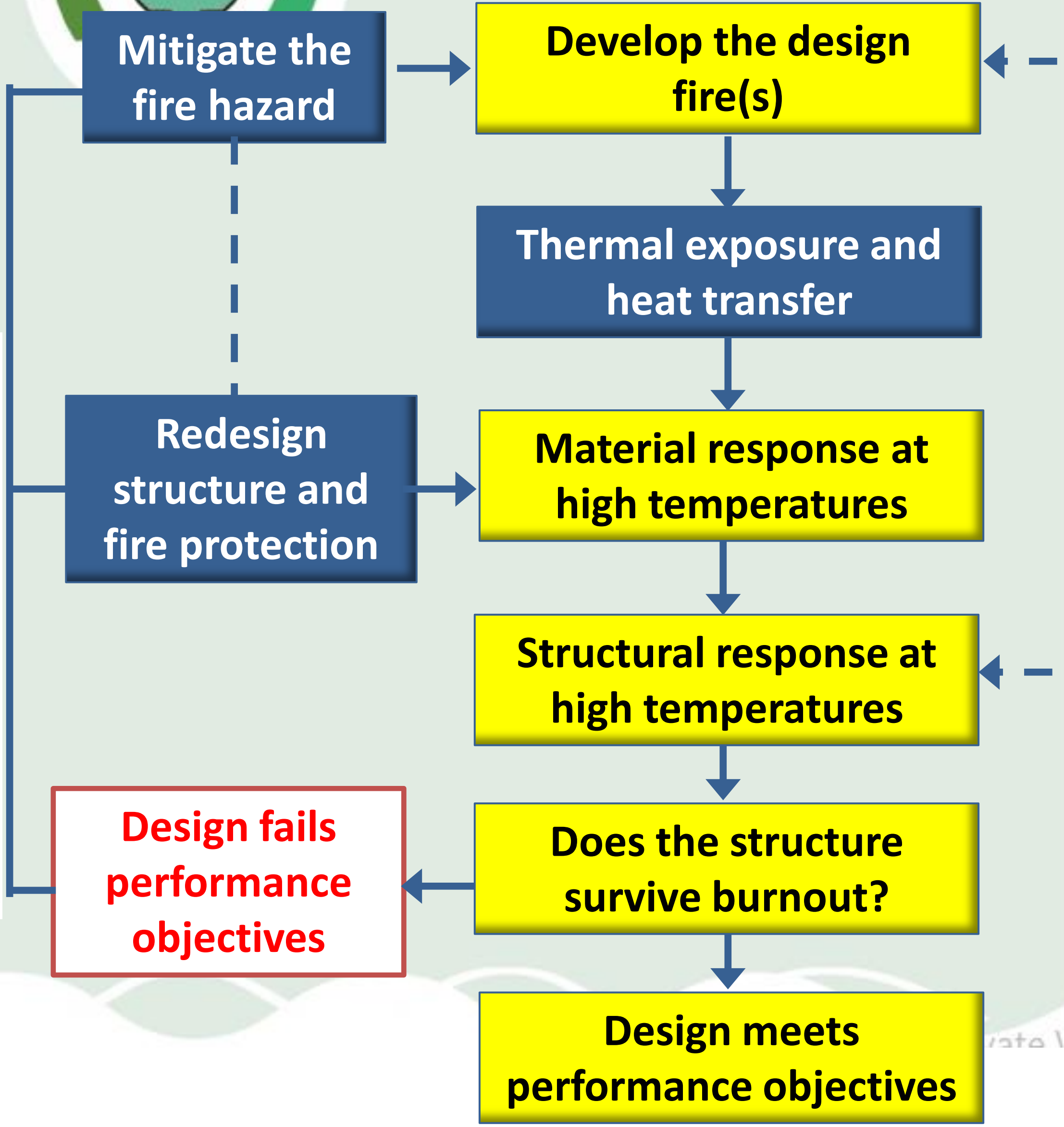
Total fire engineering design

Combustible construction:

Mitigate the fire hazard



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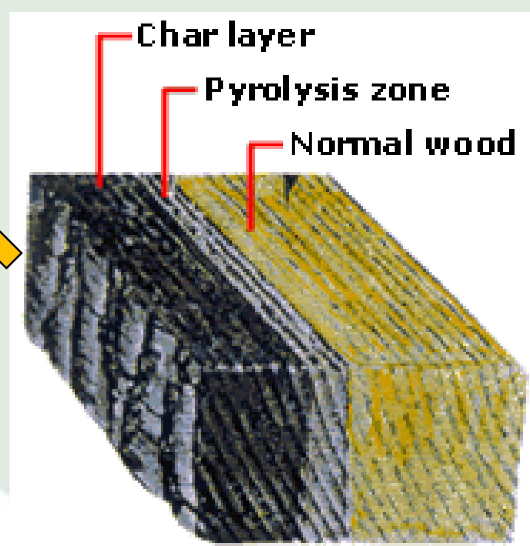
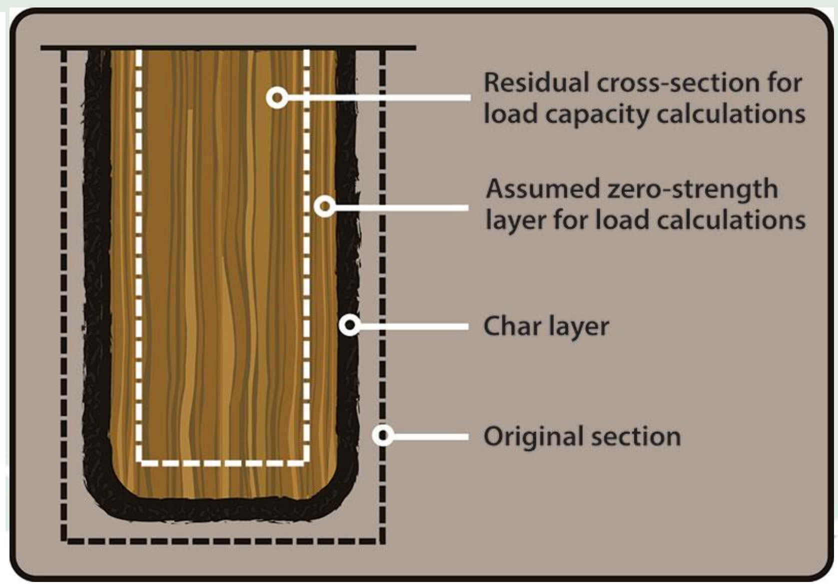
Timber in fire

Charing of timber

- The inner un-charred core remains cold and keeps its initial properties;
- Since charcoal is produced at a constant rate, the time to failure of timber construction elements can be easily predicted.

λ = 0,02 W/mK

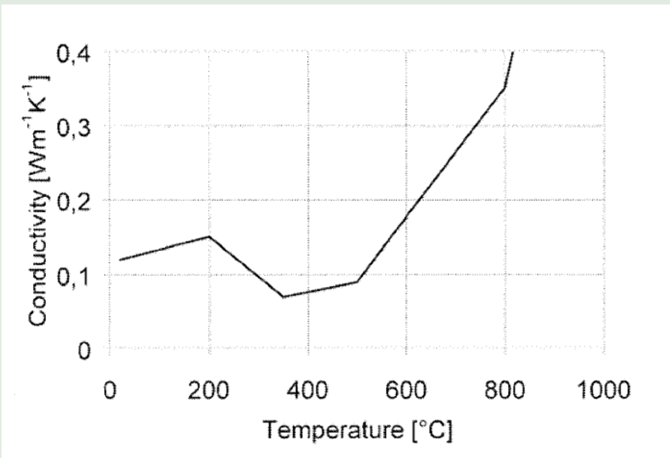




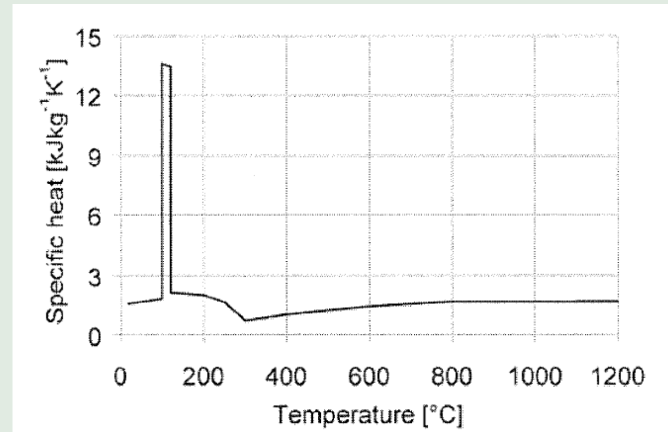
Timber in fire

Thermal characteristics

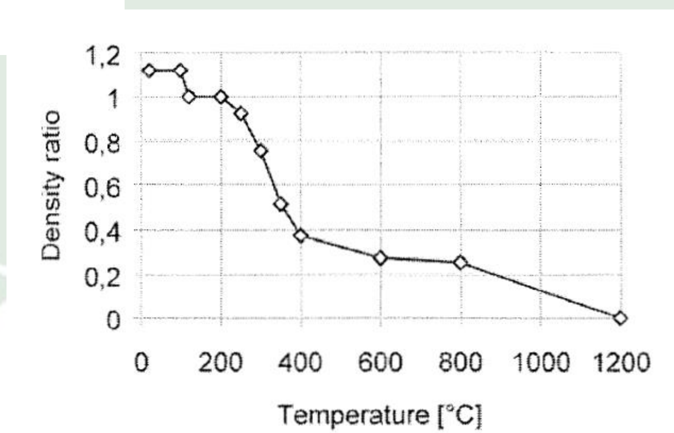
Timber thermal properties are strongly affected by temperature and moisture content levels. According to EN 1995-1-2:



Temperature-thermal conductivity relationship



Temperature-specific heat relationship



Temperature-density ratio relationship for softwood with an initial moisture content of 12 %

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Timber in fire

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Strength characteristics and design

Timber is categorised as either ‘softwood’ or ‘hardwood’.

Timbers of similar **strength properties** are grouped together into a series of strength classes which are defined in **EN 338**.

Two methods may be used **to evaluate the required fire resistance** of timber structural members:

- the reduced cross-section method
- the reduced properties method.

The design strength (and correspondingly the design modulus of elasticity and shear modulus) of timber members and the design procedure is given and used according to the **EN 1995-1-2.**

Rock wool in fire

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The effectiveness of rock wool in reducing heat transfer depends upon its structural properties such as density, thickness, composition and the fineness of the wool as well as the temperature at which it is used.

Due to its **non-combustibility** rock wool insulation does not spread fire by releasing heat, smoke, or burning droplets. In fire environment it retains integrity and hampers the fire process. The maximum working temperature is about 750°C and melting occurs at 1000 °C.

Rock wool is used to:

- protect the flammable constructions or those susceptible to the effects of fire;
- to increase the structural elements resistance to fire;
- to slow down the heat transfer in case of high temperatures.

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Gypsum board in fire

Gypsum is porous and non-homogeneous material which contains chemically combined water (**approximately 50% by volume**).

When gypsum panels are exposed to fire, dehydration reaction occurs **at 100ºC to 120ºC.**

There are three types of gypsum boards:

- **Regular boards** (used as non-fire resistant partitions);
- **Type X gypsum boards**, special glass fibers are intermixed with the gypsum to reinforce the core of the panels and reduce the size of the cracks.
- **Type C gypsum boards** core contains glass fibers, but in a much higher percent by weight, as well as vermiculite, which acts as a shrinkage-compensating additive that expands when exposed to elevated temperatures of a fire.

Case study 1

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FIRE RESISTANCE OF PROTECTED AND UNPROTECTED TIMBER BEAMS

Case study 1

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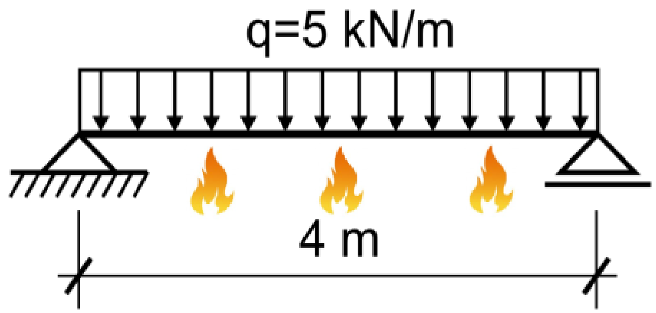
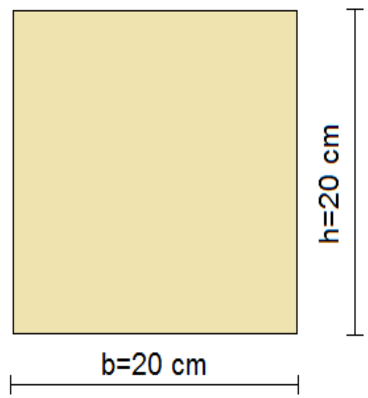
Description of the problem



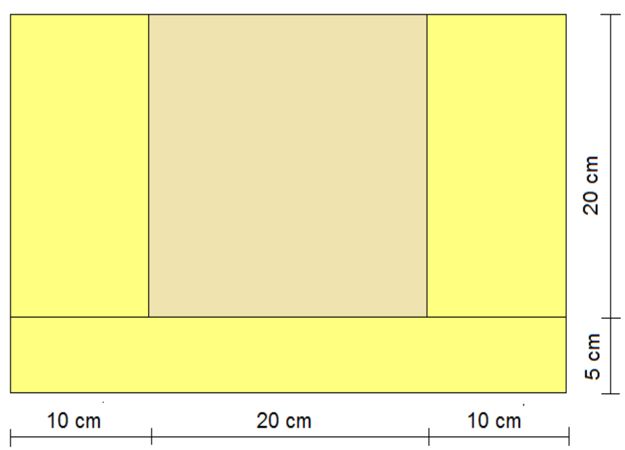
Standard fire curve ISO 834:

$$T=20+345\log_{10}(8t+1)$$

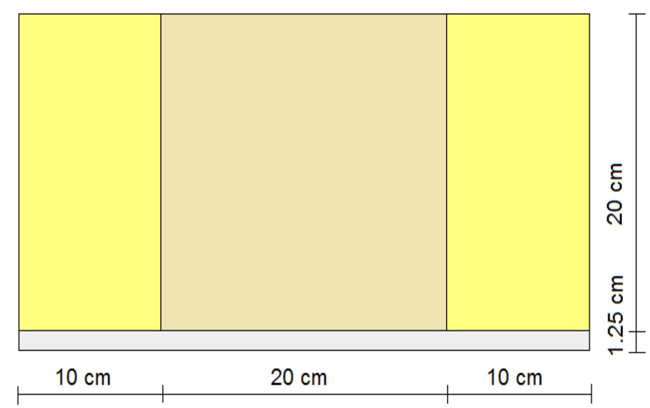
Case study 1



Case study 2



Case study 3



Legend

- timber
- rock wool
- gypsum board

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Case study 1

Description of the problem

- The characteristic values of the strength, stiffness and density of the timber beam, strength class C30, is taken in accordance with the EN 338. The material was considered with 12% moisture content.
- The X type gypsum board has a density of 648 kg/m^3 and the rock wool has a density of 160 kg/m^3.

Temperature dependant thermal conductivity and specific heat for the materials are taken in accordance with the appropriate EC parts for the materials.

Thermal property	Unit	Timber	Type X gypsum board	Rock wool
λ (20 °C)	[W/mK]	0.12	0.40	0.037
c (20 °C)	[J/kgK]	1530	960	880
ρ (20 °C)	Kg/m^3	425	648	160
α_c	[W/m^{2}K]	25	25	25
$\alpha_{c, cold}$	[W/m^{2}K]	4	/	/
ε		0.8	0.9	0.75

Case study 1
Thermal analysis

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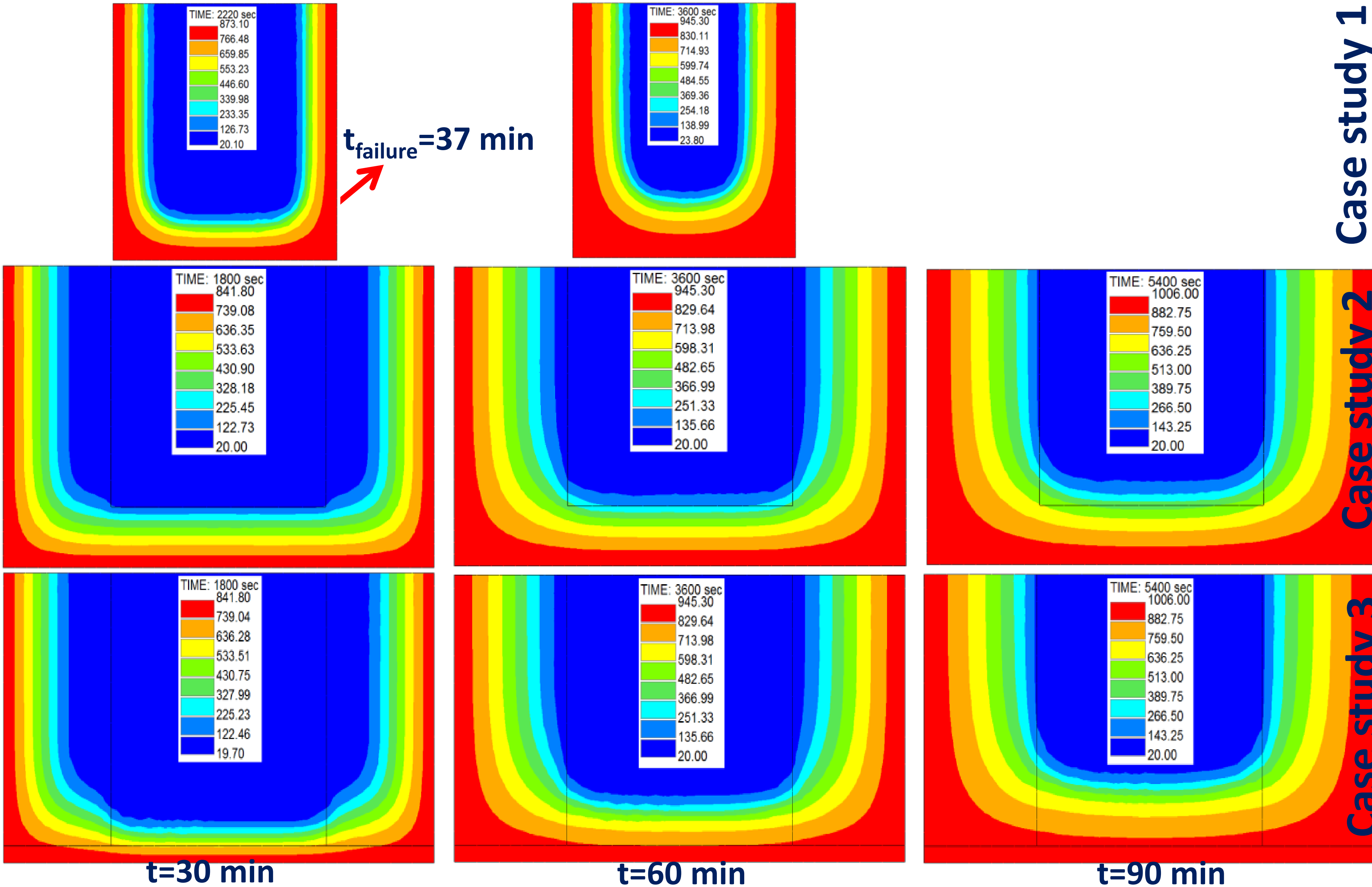

Case study 1

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Charring depths and charring rates

According to the simplified analytical reduced cross-section method given in Eurocode 1995-1-2, the effective charring depth in the cross-section of the unprotected timber beam is calculated using the following relations:

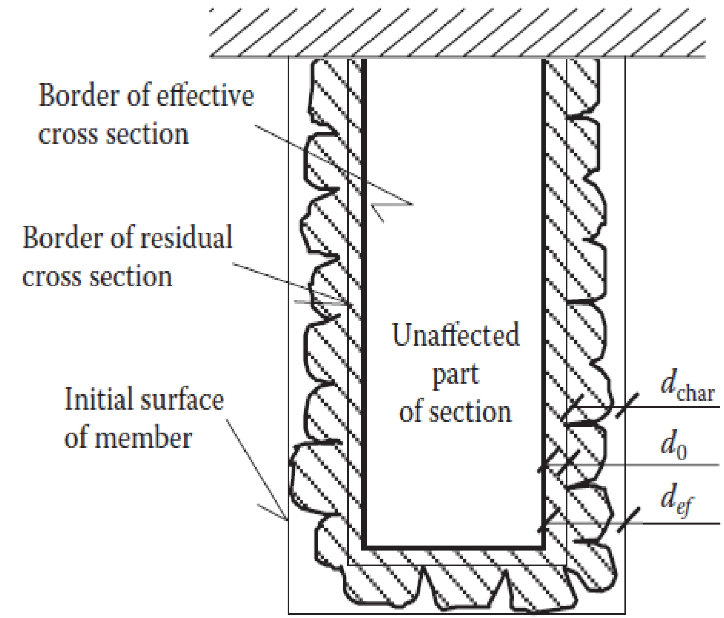
$d_{ef}=\beta_n*t+k_0*d_0=36.6\ mm$

$b_{fi}=b-2*d_{ef}=126.8\ mm$

$h_{fi}=h-d_{ef}=163.4\ mm$

$A_r= b_{fi} * h_{fi} =0.020719\ m^2$

$A_r(\%A)=51.8\%$



where:

$\beta_n = 0.8\ mm/min$ is the design notional charing rate under Standard fire exposure.

$t=37\ min$ is the time of fire exposure

$k_0=1$ is for fire exposure t>20 min

$d_0=7\ mm$ is the zero strength layer

A_r is the area of the reduced cross section

Case study 1

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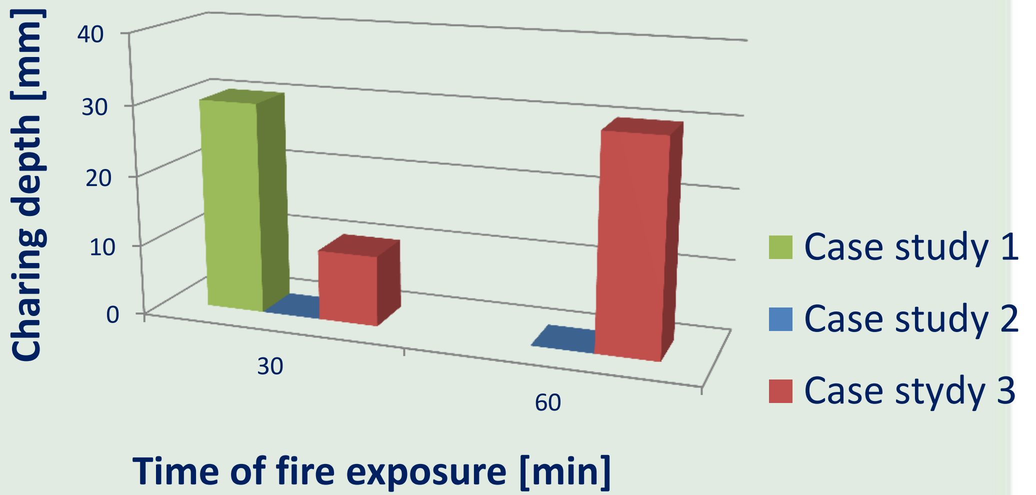
Charring depths and charring rates

From the numerical analysis at $t_{failure}$=37 min:

- the charring depth in the horizontal direction is d_{char}=30.2 mm and in the vertical direction h_{char}=30.1 mm.
- the charring rates (the ratio of the charring depth to the time of fire exposure) are β_b=0.82 mm/min and β_h=0.81 mm/min, respectively.

<u>Note</u>:
Charring depth is the distance between the outer surface of the original cross section and the position of the char-line. The position of the char-line is taken as the position of the 300-degree isotherm.

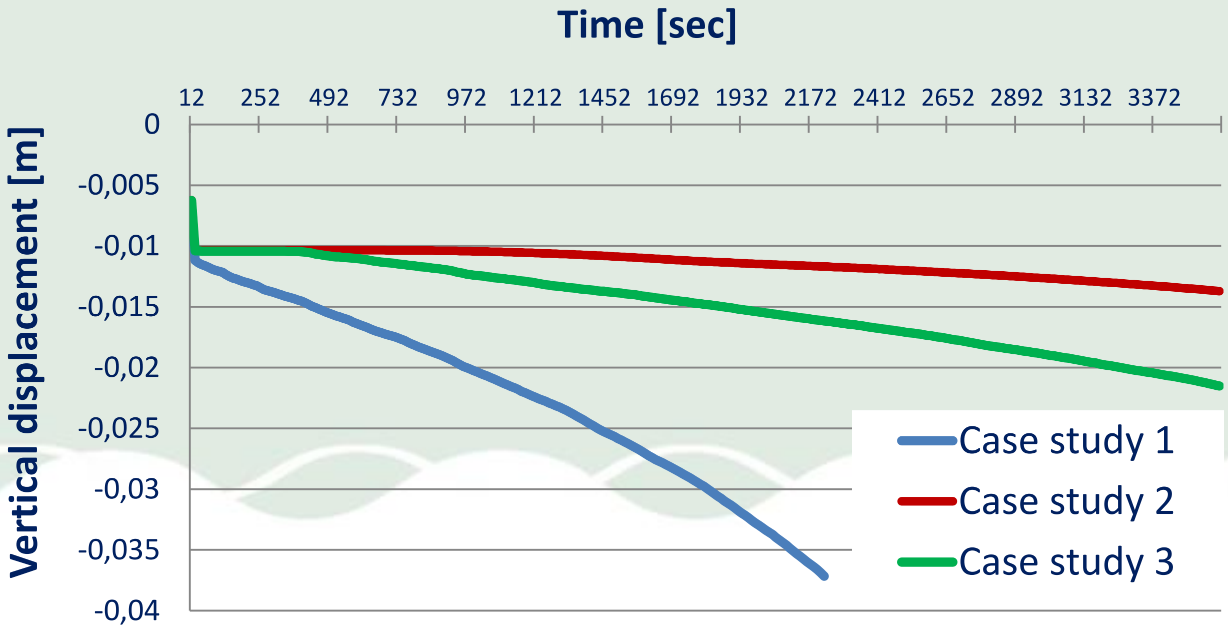
Compaison of cahring depts in vertical direction for different Case studies



Case study 1
Structural analysis

Vertical displacements at mid-span of the beams

Type of cross section	Δy [cm]	Time [min]
Case study 1	3.72	37
Case study 2	1.37	60
Case study 3	2.15	60



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Case study 2

FIRE RESISTANCE OF PROTECTED AND UNPROTECTED TIMBER COLUMNS

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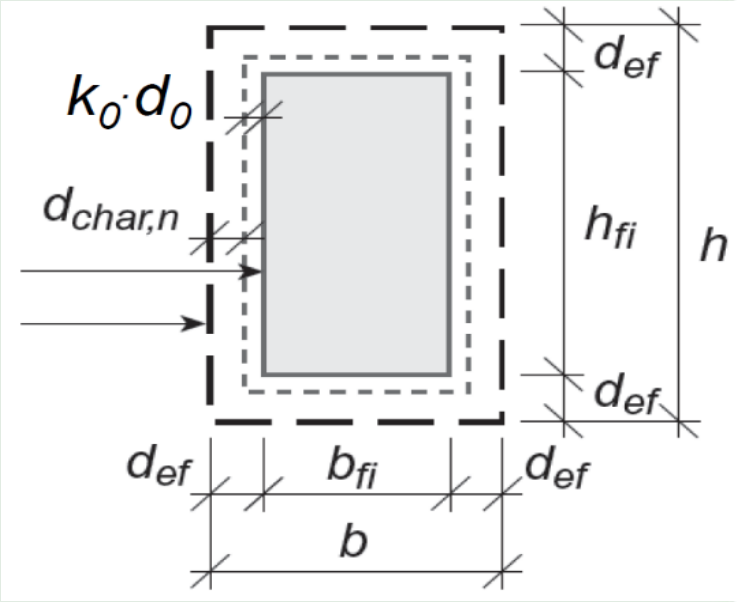
Case study 2

Unprotected timber columns in fire

- Cross-section dimensions 16x16, 18x18, 20x20, 22x22, 24x24, 26x26cm,
- Height H=3m, pin ended on both sides,
- Subjected to axial loading,
- Exposed to Standard fire ISO 834 from all four sides.
- Timber type C 24 with specific density γ_d=600 kg/m^3
- Fire resistance classes: R30, R45, and R60.
- **reduced cross-section method** was used



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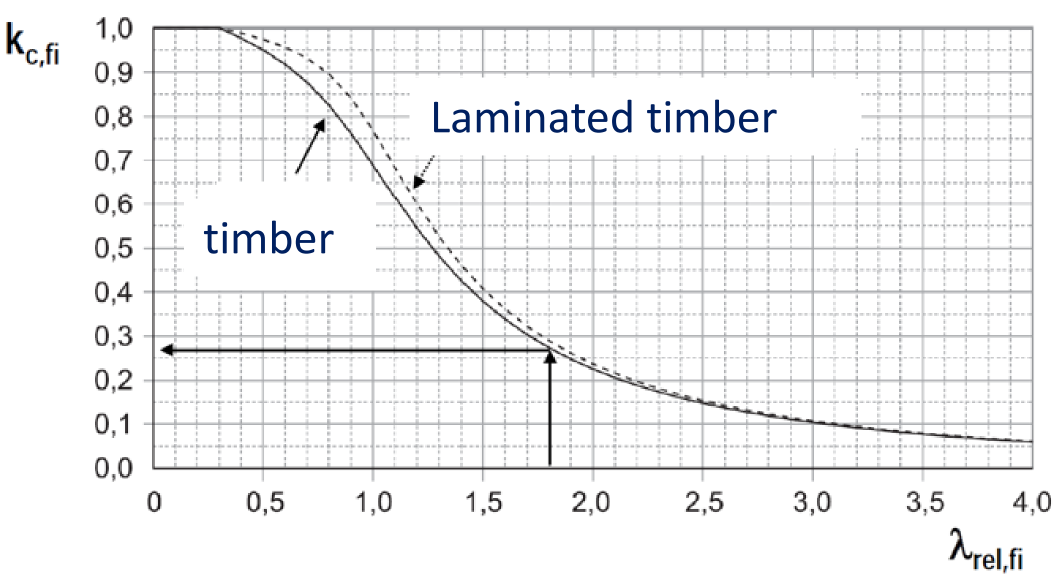
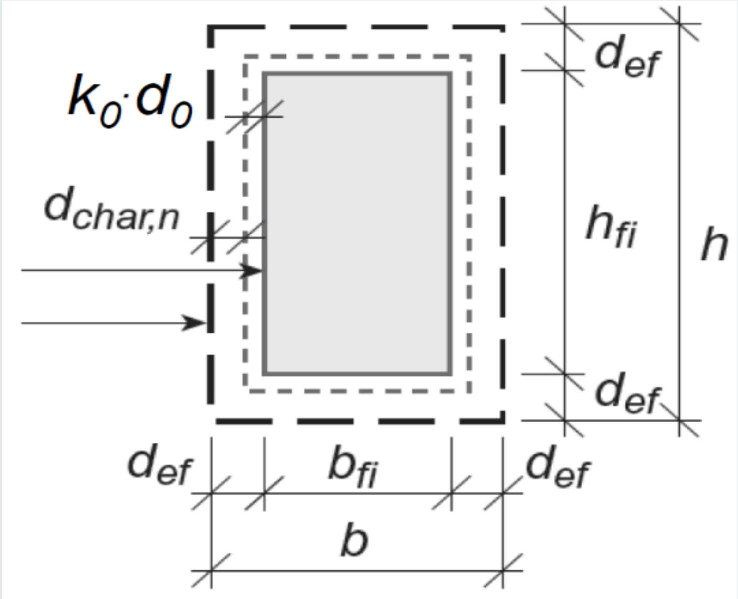
Case study 2

Unprotected timber columns in fire

The design compressive strength of the column in fire, $f_{c,0,d,fi}$, is reduced as a result of the increased buckling effect due to the reduced cross section dimensions of the column by forming the char layer.

$$f_{c,0,d,fi} = k_{c,fi} * k_{fi} * f_{c,0,k}$$





Design compressive stress in fire, $\sigma_{d,fi}$, is increased as a result of reduced cross section dimensions

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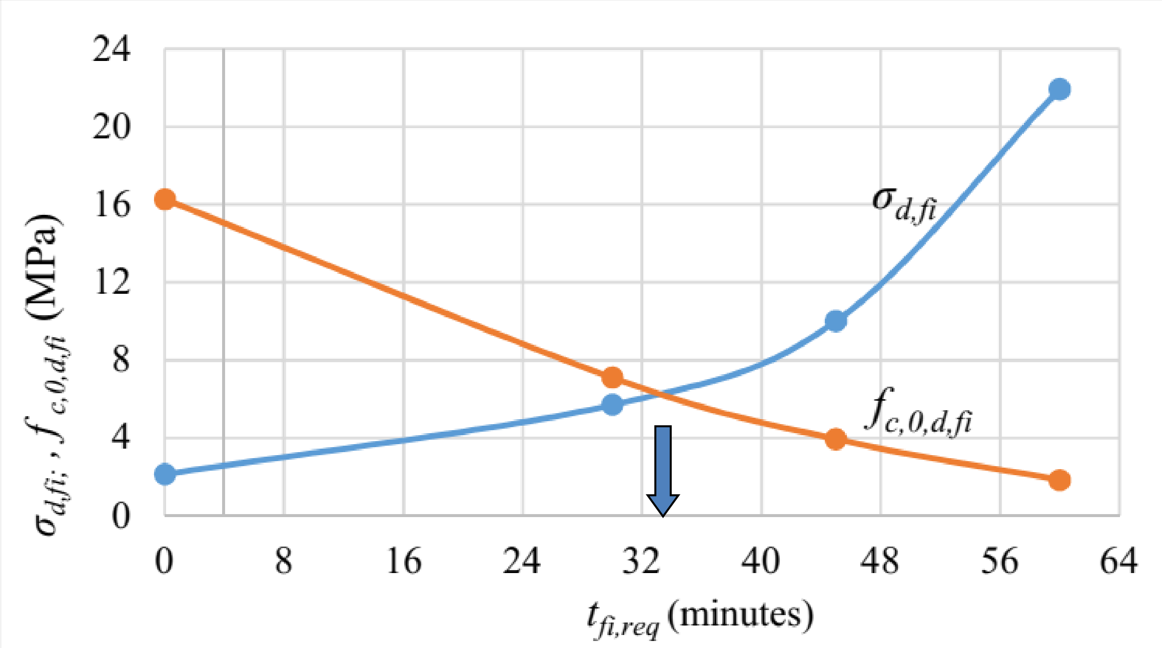
Case study 2

Unprotected timber columns in fire



Fire resistance of unprotected column with cross section dimensions **16x16cm,** hight **H=3m**, pin ended on both sides

this column satisfies the criteria for R30 class of fire resistance.

Cross section dimensions (cm)	16x16	17x17	18x18	20x20	22x22	24x24
Fire resistance (minutes)	33	39	46	59	70	82

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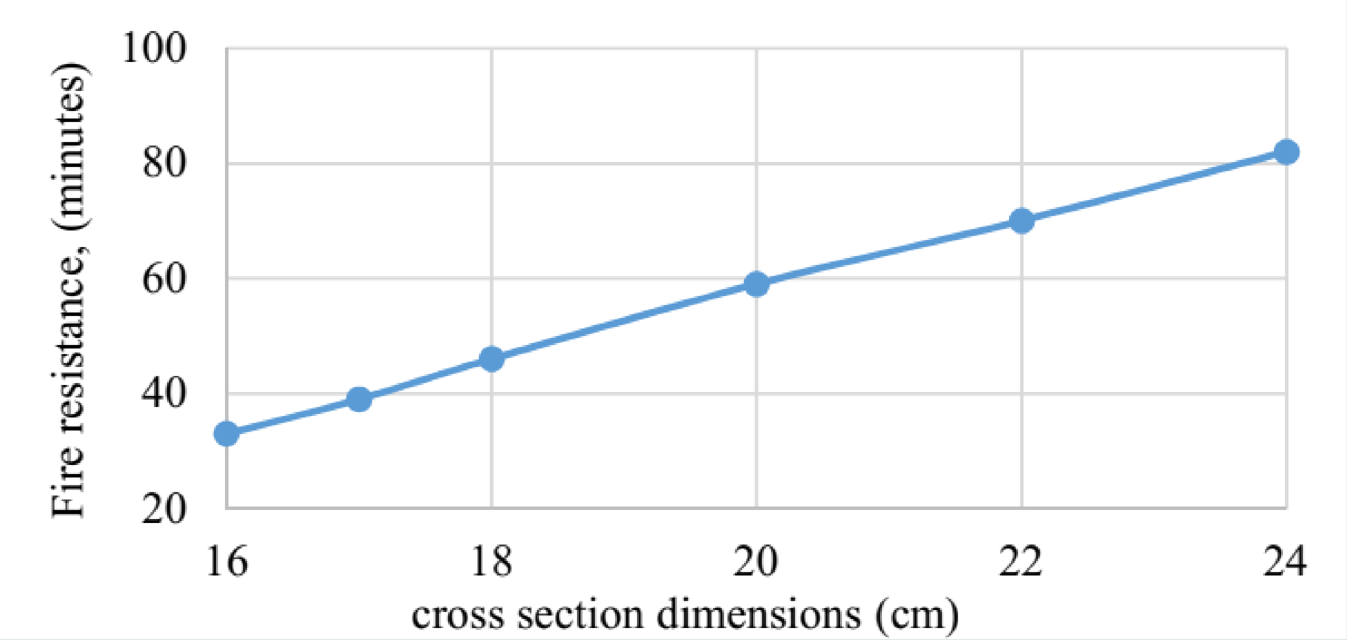
Case study 2

Unprotected timber columns in fire

Fire resistance of unprotected columns with hight H=3m, as function of the cross section dimensions



In case of constant axial force the fire resistance of the unprotected timber column **increases proportionally** to the increase of the cross section dimensions. The reason for this fact is the **constant charring rate of the timber.**

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Case study 2

Protected timber columns in fire

The influence of two different types of thermal protection was analyzed:

- wood-based panels
- one or two layers of gypsum plasterboard.

Dimensions of the analyzed columns are: 16x16,18x18 and 20x20cm.

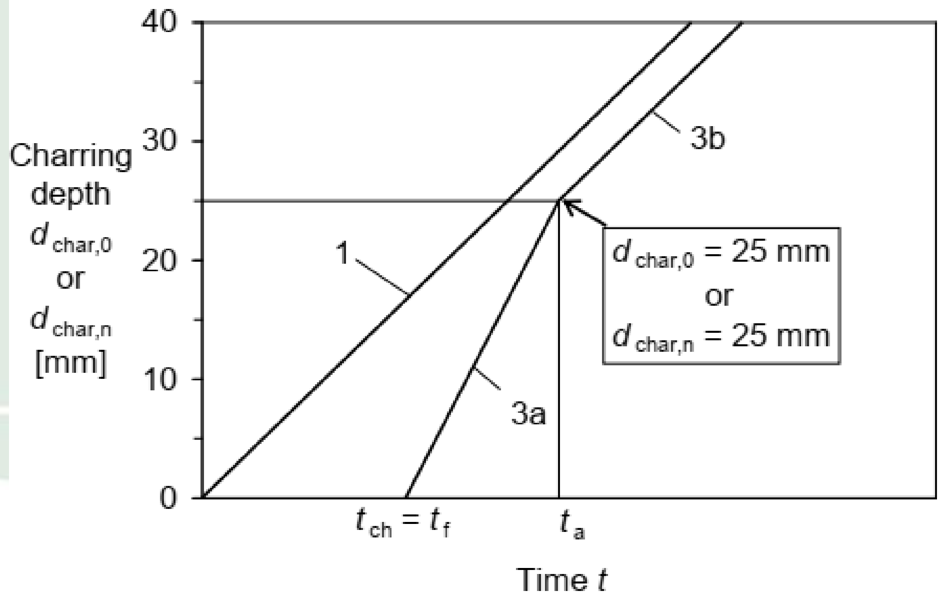
- wood-based panels:

$$t_{ch} = h_p/\beta_o$$

- one or two layers of gypsum plasterboard:

$$t_{ch} = 2{,}8 * h_p - 14$$

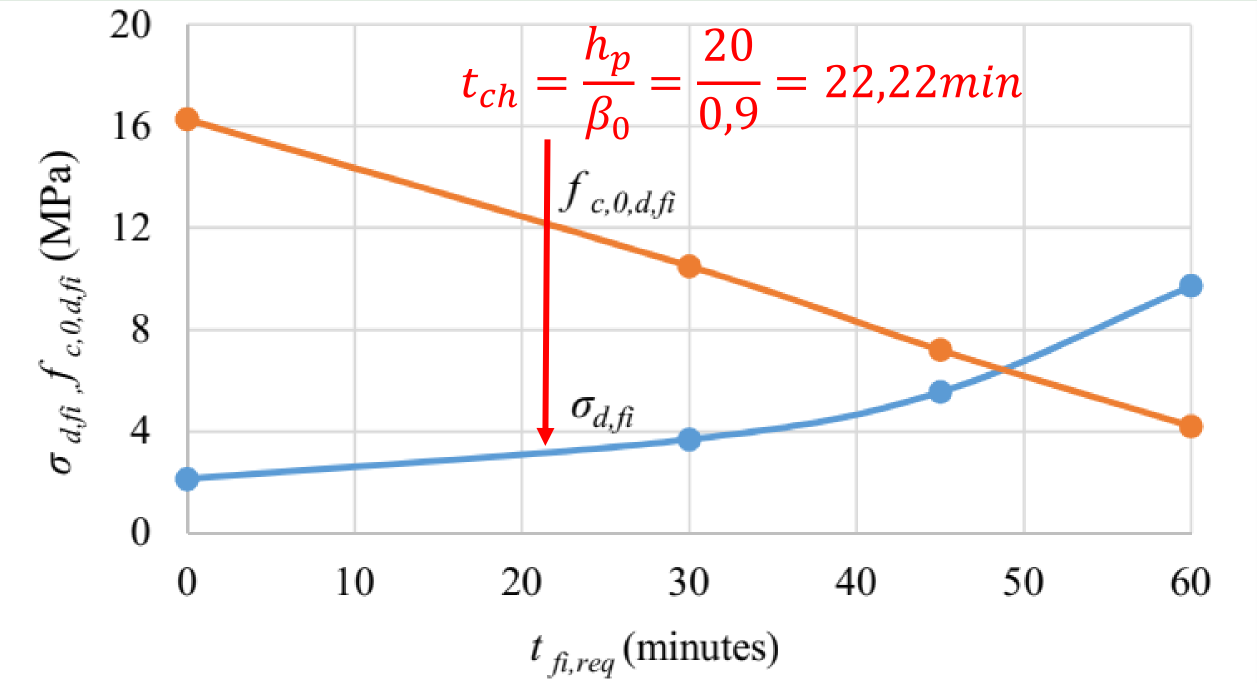
$$t_{ch} = 2{,}8 * (h_{p1} + 0.5 * h_{p2}) - 14$$



Case study 2

Protected timber columns in fire

Fire resistance of column with cross section dimensions 16x16cm, hight H=3m, pin ended on both sides, protected by one layers of wood-based panel



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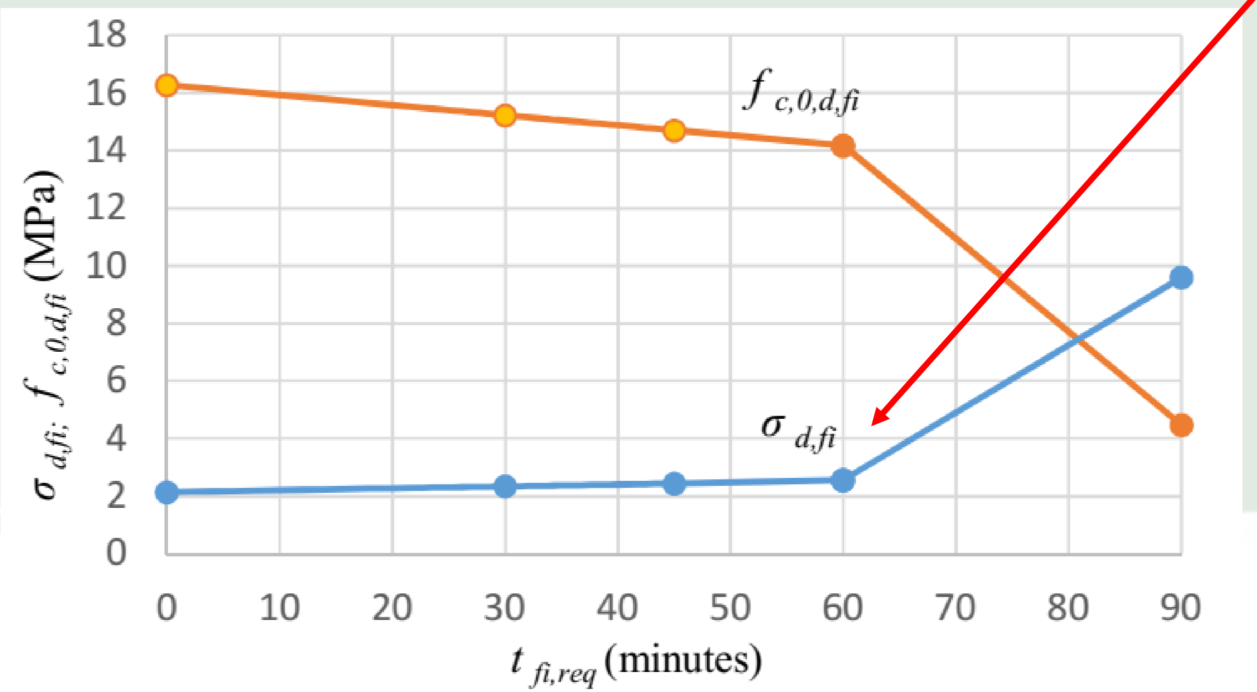
Case study 2

Protected timber columns in fire

. Fire resistance of column with cross section dimensions 16x16cm, hight H=3m, pin ended on both sides, protected by two layers of gypsum plasterboard

$$t_{ch} = 2{,}8 * (h_{p1} + \frac{1}{2} * h_{p2}) - 14 = 2{,}8 * (18 + \frac{1}{2} * 18) - 14 = 61{,}6\ min$$



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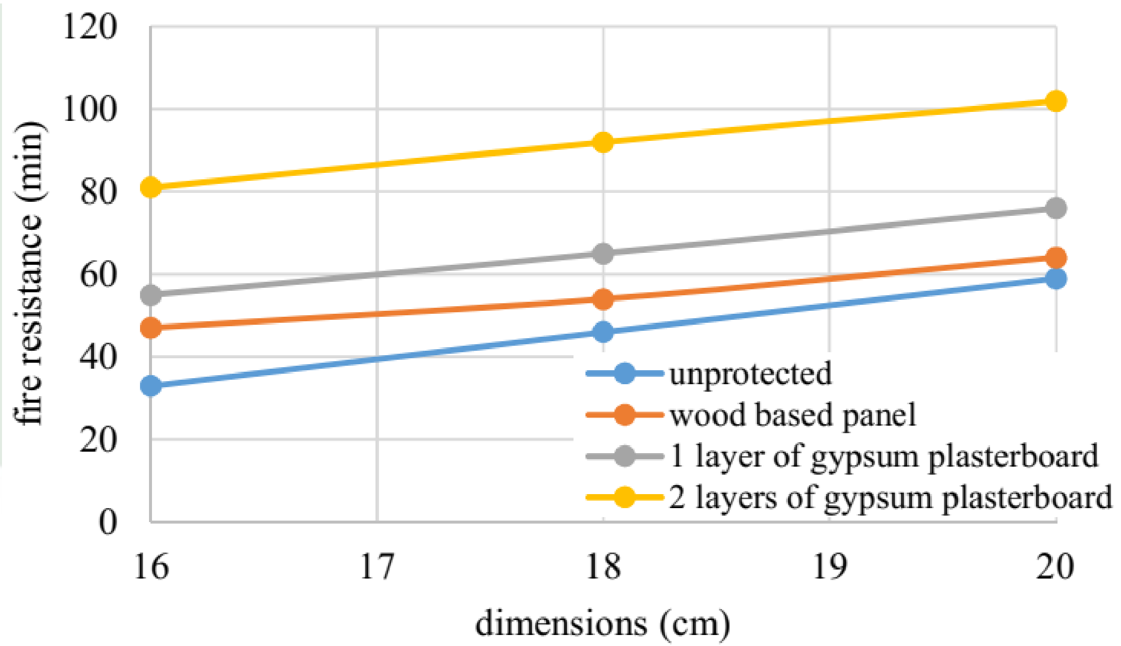
Case study 2

Protected and unprotected timber columns in fire

Cross section dimensions (cm)	Fire resistance (minutes)			
	unprotected	Protected by one layer of wood-based panel	Protected by one layer of gypsum plasterboard	Protected by two layers of gypsum plasterboard
16x16	33	48	55	81
18x18	36	53	65	91
20x20	59	64	76	102



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Conclusions

- **The acceptable fire performance of unprotected timber elements is attributed to the charring effect of timber.** The char layer acts as an insulator and protects the core of the timber section. For the required duration of fire exposure, unprotected elements may withstand the design loads only if proper dimensions of the cross-section are used.
- **Fire exposed elements protected with gypsum fireboards show improved fire resistance, but best results are achieved when the protection material is rock wool.**
- In practice, if there are no architectural requirements for visibility of timber elements, floor and roof timber structures should be protected with rock wool not only to satisfying the energy efficiency requirements, but to ensure the required fire resistance and fire safety.
- **The general conclusion is that a fire safety plan with all fire safety measures has to be prepared for the timber structures and careful planning and detailing of the structural elements to be conducted.**

Case study 3

FIRE RESISTANCE OF ENERGY EFFICIENT FLOOR STRUCTURES

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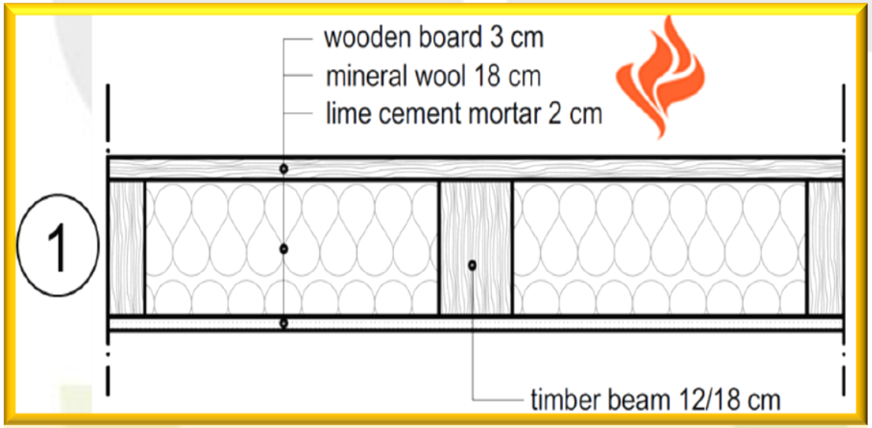
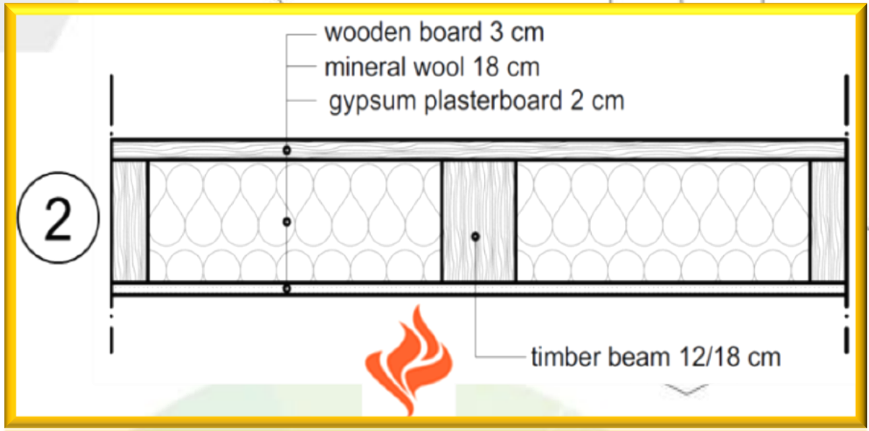
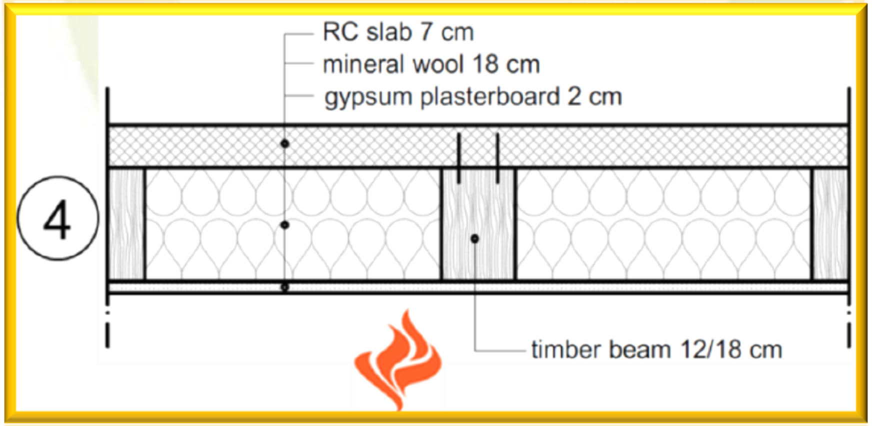
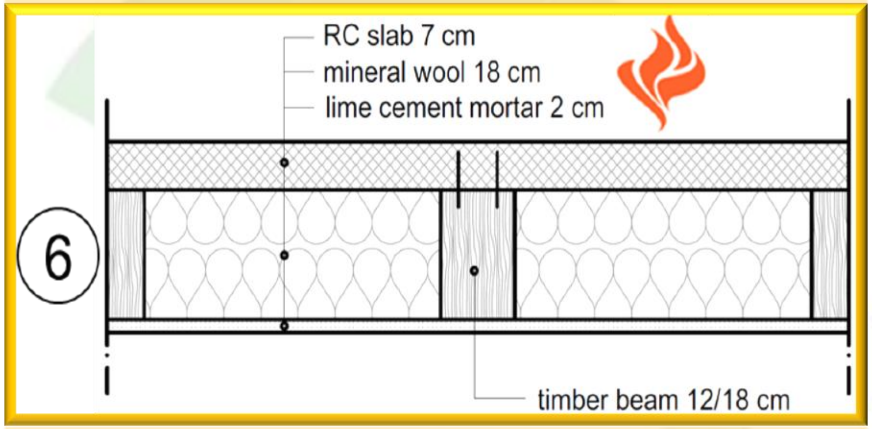
FIRE RESISTANCE OF TIMBER BASED FLOOR STRUCTURES

- Timber-concrete composite floor structure TCCFS
- Traditional timber floor structure TFS
- Two different fire scenarios









ANALYZED TIMBER BASED FLOOR STRUCTURES

- Case 1: TFS with ceiling made of lime cement mortar, fire at the top side
- Case 2: TFS with ceiling made of gypsum plasterboard, fire at the bottom side
- Case 3: TFS with ceiling made of lime cement mortar, fire at the bottom side
- Case 4: TCCFS with ceiling made of gypsum plasterboard, fire at the bottom side
- Case 5: TCCFS with ceiling made of lime cement mortar, fire at the bottom side
- Case 6: TCCFS with ceiling made of lime cement mortar, fire at the top side.

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CHARACTERISTICS OF THE FLOOR STRUCTURES

Material properties of composite materials at room temperatures

Material properties		Concrete	Wood	Gypsum	Mortar	Miner. wool
specific mass	kg/m^3	2400	450	900	1850	150
water percentage	%	8	4	4	8	2
convection coeff. on hot side	W/m^2K	25	25	25	25	25
convection coeff. on cold side	W/m^2K	9	9	9	9	9
relative emissivity	-	0,8	0,8	0,85	0,8	0,85
specific heat	J/kgK	900*	1530*	1090	400	150
thermal conductivity	W/mK	1,6*	0,12*	0,21	0,87	0,035

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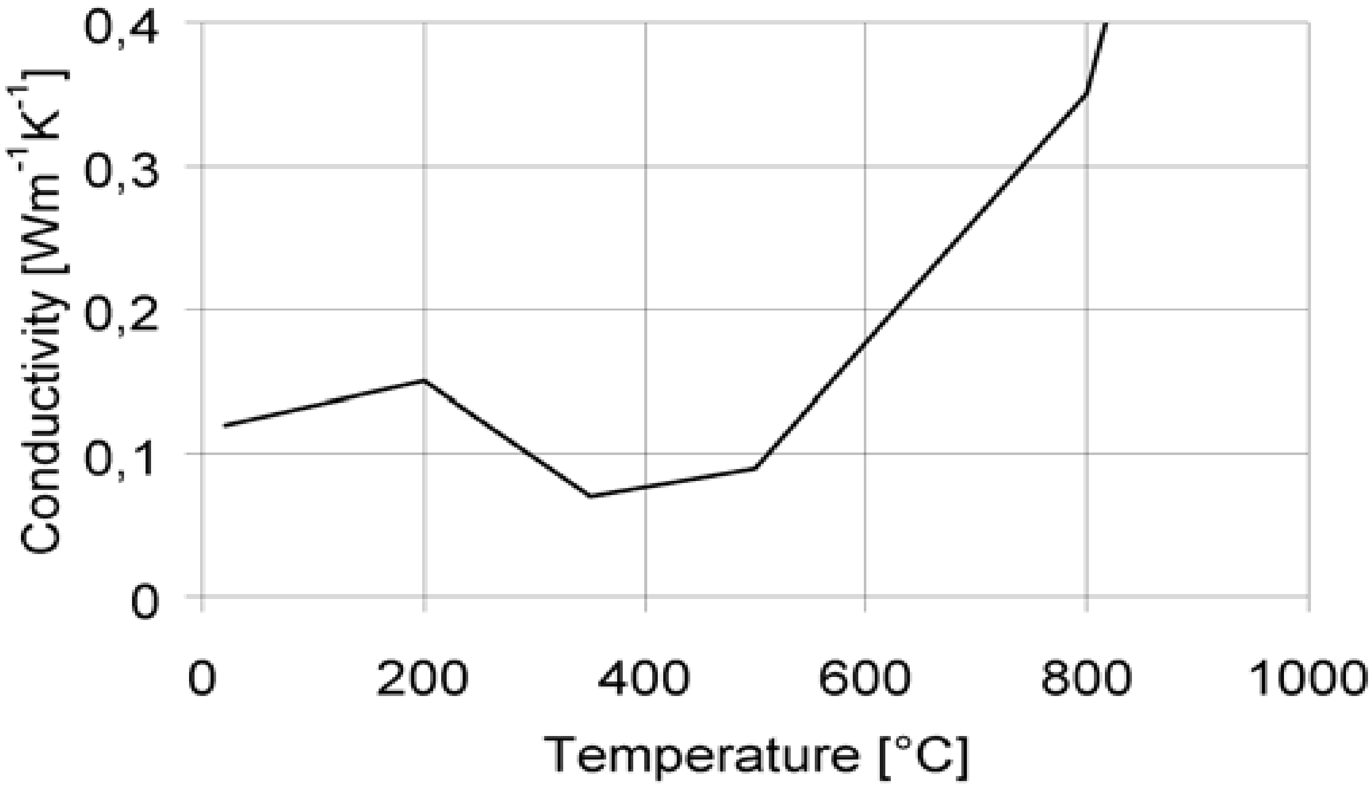
TEMPERATURE-THERMAL CONDUCTIVITY RELATIONSHIP FOR WOOD AND THE CHAR LAYER, ACCORDING TO EN 1995-1-2



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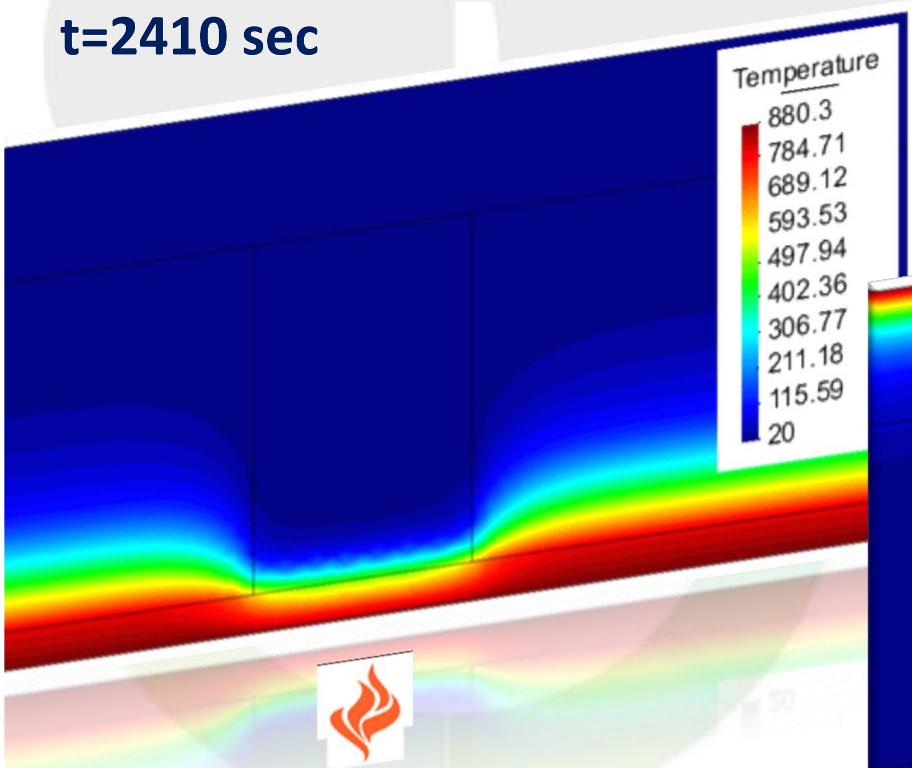
TEMPERATURE DISTRIBUTION IN THE CROSS SECTION OF TIMBER-CONCRETE COMPOSITE FLOOR STRUCTURE WITH GYPSUM PLASTERBOARD CEILING, AT THE MOMENT OF FAILURE (WHEN q_{fi}/q_u= 0.8)

t=2410 sec



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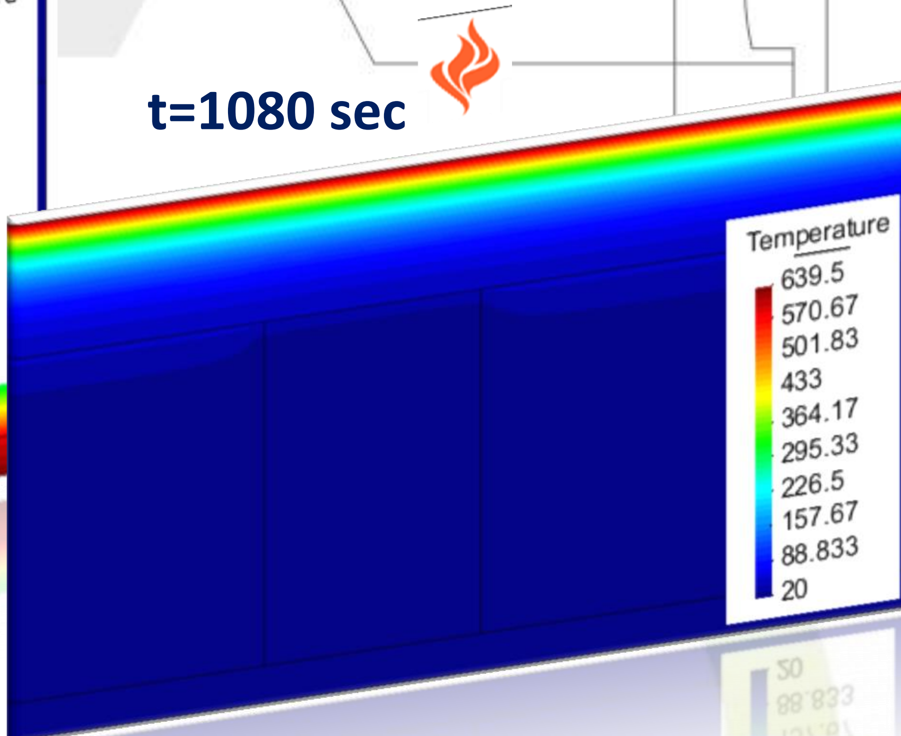

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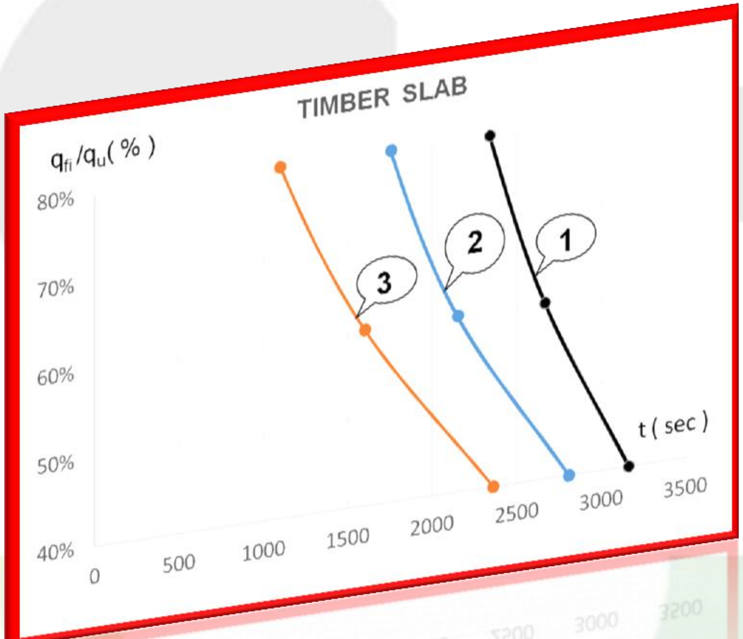
THE EFFECT OF THE INTENSITY OF THE PERMANENT ACTION AND THE POSITION OF THE ISO 834 STANDARD FIRE ON THE FIRE RESISTANCE OF THE TWO TYPES OF SIMPLY SUPPORTED FLOOR STRUCTURES



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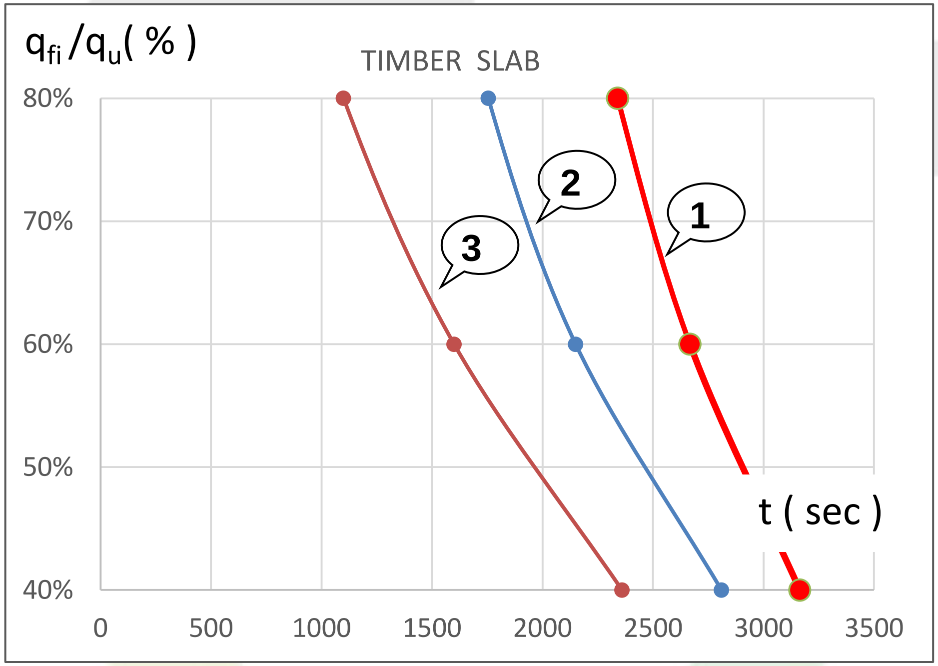
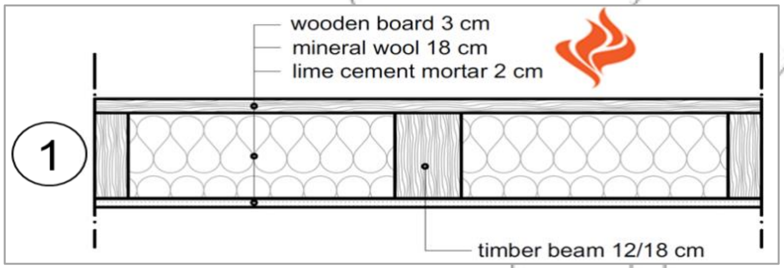
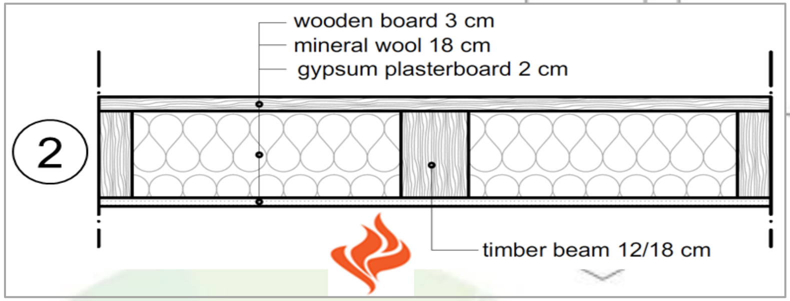
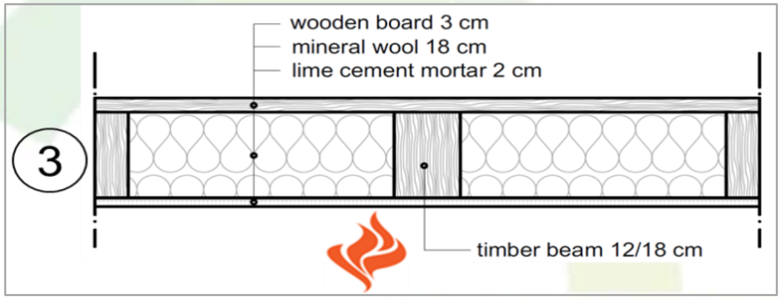
THE EFFECT OF THE INTENSITY OF THE PERMANENT ACTION AND THE POSITION OF THE ISO 834 STANDARD FIRE ON THE FIRE RESISTANCE OF SIMPLY SUPPORTED TIMBER FLOOR STRUCTURE









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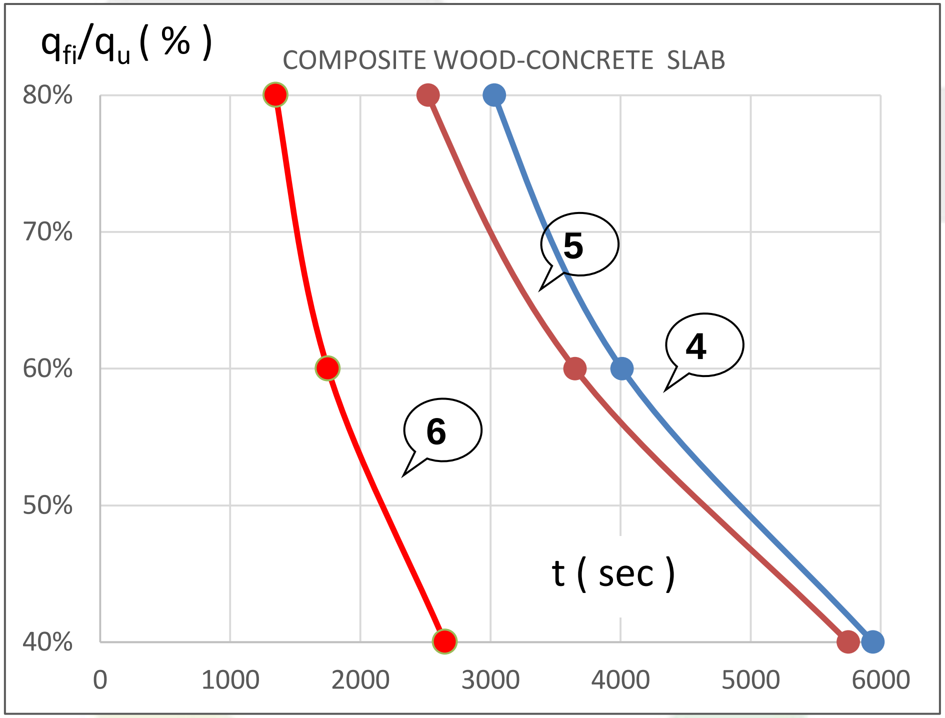
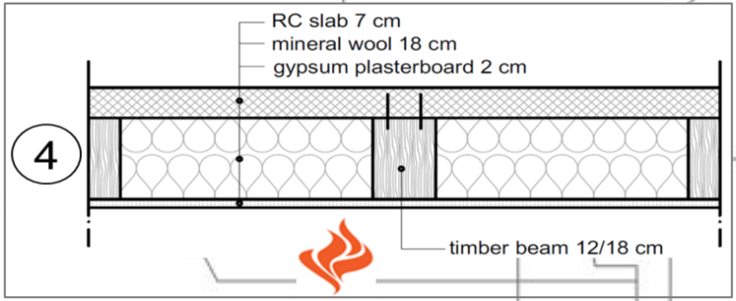
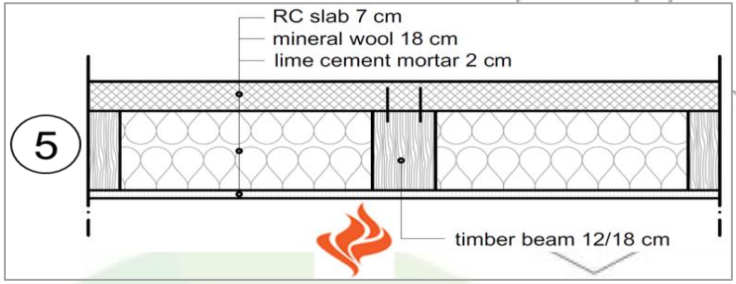
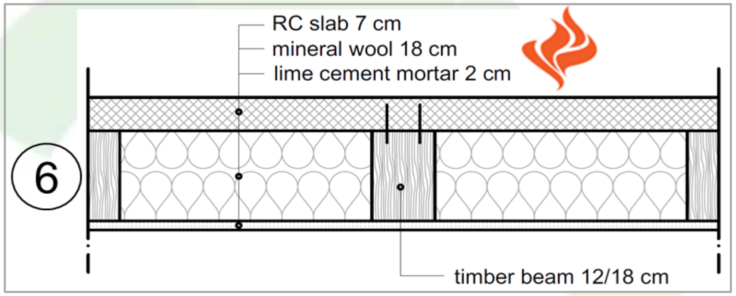
THE EFFECT OF THE INTENSITY OF THE PERMANENT ACTION AND THE POSITION OF THE ISO 834 STANDARD FIRE ON THE FIRE RESISTANCE OF SIMPLY SUPPORTED COMPOSITE FLOOR STRUCTURE









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Thank you for your attention!

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