CONSTRUCTION MATERIALS FOR SUSTAINABLE FUTURE

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IMPRESSUM

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ensuring its fire safety. Nowadays, the fire safety of a building is considered as an essential part of the Declaration of performance [3].

As building technologies and science evolve, the timber fire protection measures are improved and upgraded. The process of making wood more fire resistant usually involves application of surface coatings or impregnation with chemical treatments. The use of rock wool, gypsum plasterboards or other fireboards, as fire-resistant linings, are also common in practice.

Nowadays, as a result of the rigorous environmental and economical requirements, as well as ensured fire resistance through appropriate design, the industries in many countries are trying to shift more public sector construction to timber.

2. BEHAVIOUR OF WOOD, ROCK WOOL AND GYPSUM PLASTER BOARD IN FIRE

2.1. TIMBER IN FIRE

Wood is a complex composite of natural polymers and is generally anisotropic, heterogeneous and porous material. The properties of wood are affected by the moisture content, which, in case of fire, evaporates and diffuses. This leads to changes of material properties [4]. When exposed to the heat of a fire, the wood goes through a process of thermal breakdown into combustible gases. The pyrolysis is a thermochemical decomposition of a wood at elevated temperatures in the absence of oxygen (or any halogen). It involves the simultaneous change of chemical composition and physical phase, and is irreversible. It usually starts at temperatures of 280 °C to 300 °C. The key contributing factor in timber's fire resistance is the layer of charcoal that is formed on the burning surface during the pyrolysis process. This charred layer acts as an insulator protecting the inner core of the timber, making it resist to heat penetration and thus burn more slowly [1]. The inner uncharred core remains cold and keeps its initial properties, enabling to continue to carry its load (Figure 6). The progressive conversion of the fire-exposed surfaces to ever-deepening char occurs at definable rates. Since charcoal is produced at a constant rate, the time to failure of timber construction elements can be easily predicted. The rate of conversion to char decreases with increasing of moisture content and density of the timber used. The charring rate is also affected by the permeability of the timber to gaseous or vapor flow. Charring normal to the grain of timber is one-half of that parallel to the grain. As long as the residual section is large with respect to the depth of char development, the rate is unaffected by the dimension of the section exposed [5].

2.2. ROCK WOOL IN FIRE

In normal temperature environment, rock wool thermal insulation prevents convection by holding air still in the matrix of the wool. Still air is a good insulator. It also stops radiation and limits the conduction of heat through the body of the insulation. 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; and to slow down the heat transfer in case of high temperatures.

2.3. GYPSUM PLASTERBOARD IN FIRE

Gypsum plasterboards are widely used in building construction. They consist of a gypsum core sandwiched between two layers of paper and can also contain other materials in small quantities such as glass fibre and vermiculite within the various proprietary products to improve their durability and performance when exposed to high temperatures.

There are three types of gypsum boards: Regular boards, Type X and Type C boards. Regular plasterboards are used as non-fire resistant partitions, while the Type X boards and Type C are used in fire-rated applications.

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 [6]. Heat is absorbed as portion of the combined water is driven off as steam i.e. calcination occurs. Thermal energy that converts the water to steam is thus diverted and absorbed, keeping the opposite side of the gypsum panels cool as long as there is crystalline water left to be converted into steam or until the gypsum panel is breached i.e. heat transmission is effectively retarded. In the case of regular gypsum board, as the crystalline water is driven off, the reduction of volume within the gypsum core causes large cracks to form, eventually causing the panel to fail due to structural integrity [7].

In Type X gypsum boards, special glass fibers are intermixed with the gypsum to reinforce the core of the panels. These fibers have the effect of reducing the size of the cracks that form as the water is driven off, thereby extending the length of time the gypsum panels resist fire without failure. Also, there are Type C gypsum boards whose core also contains glass fibers, only in a much higher percent by weight. In addition to the greater amount of glass fiber, the core of the Type C panels can also contain vermiculite, which acts as a shrinkage-compensating additive that expands when exposed to elevated temperatures of a fire. This expansion occurs at roughly the same temperature as the calcination of the gypsum in the core. It allows the core of the Type C panels to remain dimensionally stable in the presence of fire, which in turn allows the panels to remain in place for a longer period of time even after the combined water has been driven off [7].

3. NUMERICAL EXAMPLES

3.1. DESCRIPTION OF THE PROBLEM

Aiming to determine the impact of fire on protected and unprotected timber beams and their behaviour in fire environment, three numerical examples were analyzed using the program SAFIR [8]. The evolution of fire temperatures over time is defined with the standard fire curve ISO 834. In all examples, the simply supported beam is fire exposed on three sides (Figure 1). In Case study 1 an unprotected timber beam is analyzed, Case study 2 analyses the same timber beam but protected on three sides with rock wool and Case study 3 analyses the timber beam protected with rock wool on the sides and X type gypsum board at the bottom. The cross-sections of the beams used in the examples are presented in Figure 2.

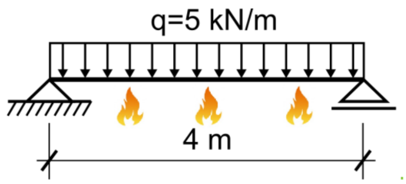

Figure 1: Geometry, support conditions and loads on a simply supported beam

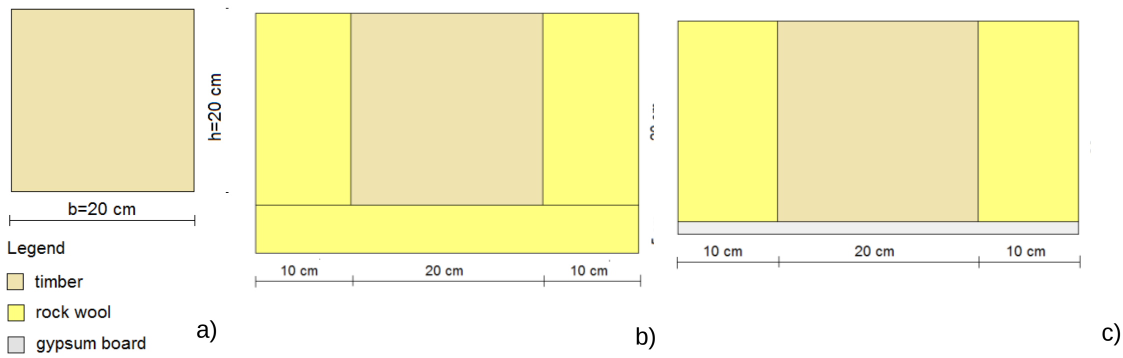

Figure 2: Cross sections of the beams, a) Case study 1, b) Case study 2, c) Case study 3

3.2. THERMAL AND MECHANICAL PROPERTIES OF MATERIALS USED IN THE NUMERICAL ANALYSIS

The characteristic values of the strength, stiffness and density of the timber beam, strength class C30, is taken in accordance with the EN 388 [9]. 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.

All thermal properties for the materials used in the analysis are given in Table 1. Temperature dependant thermal conductivity and specific heat for the materials are taken in accordance with the appropriate EC parts for the materials.

Table 1: Thermal properties used in the numerical analysis

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

3.3. THERMAL ANALYSIS

As expected, significant differences in the time-dependant temperature fields in the cross-sections of the unprotected and the protected beams were noticed. The temperature distributions in the cross-sections of all analyzed case studies, for the specific time moments or for the usually required fire resistances, given in the regulations, are shown in Figure 3, Figure 4 and Figure 5.

In Case study 1 (Figure 3), the unprotected timber beam reaches high temperatures in relatively short time period and at the moment of failure (t_f=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. This implies that 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. Charring depth is the distance between the outer surface of the original cross section and the position of the char-line (see Figure 6). The position of the char-line is taken as the position of the 300-degree isotherm.

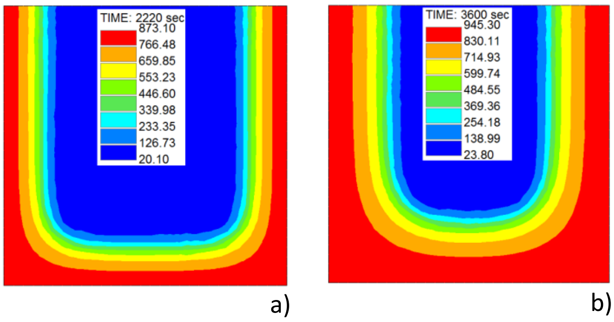

Figure 3: Temperature distribution in the cross-section of Case study 1, a) $t_{failure}$=37 min b) t=60 min

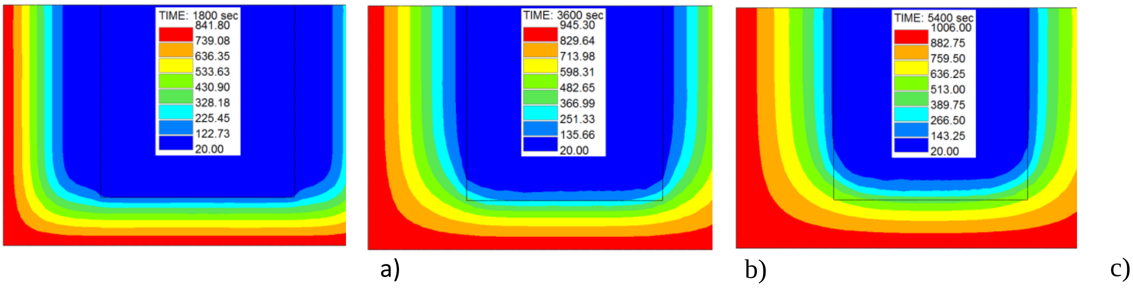

Figure 4: Temperature distribution in the cross-section of Case study 2, a) t=30 min b) t=60 min 2 c) t=90 min

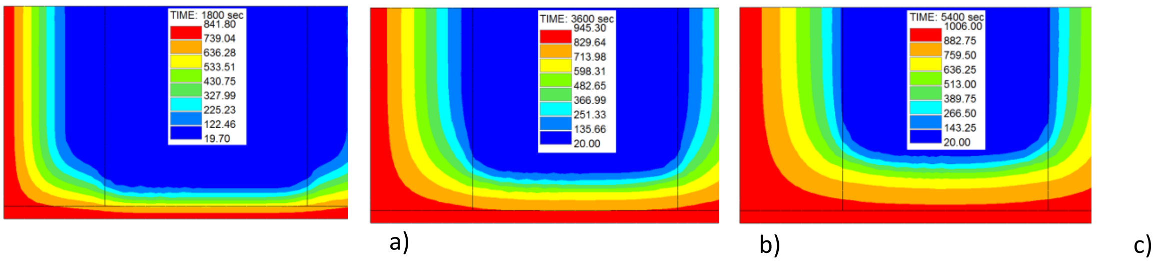

Figure 5: Temperature distribution in the cross-section of Case study 3 a) t=30 min b) t=60 min 2 c) t=90 min

According to the simplified analytical reduced cross-section method given in Eurocode 5-1-2 [10], the effective charring depth in the cross-section of the unprotected timber beam in Case study 1 can be calculated by 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

It can be see that the charring rates calculated analytically and numerically match.

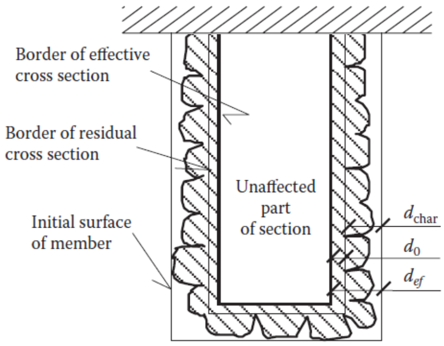

Figure 6: Definition of the residual and the effective cross-section

In case of protected timber beams, i.e. Case study 2 and Case study 3, the moment when charring process starts is delayed (Figure 4 c and Figure 5 a) and only the numerical results are presented.

At 30 minutes of fire exposure, the whole cross-section of the timber beam in Case study 2 is cold (Figure 4 a). At the same time, the timber beam in Case study 3 has 10 mm charring depth in the vertical direction of the cross-section while the sides of the section remain unheated because of the positive influence of the rock wool insulation (Figure 5 a). At time t=37 min the cross-section of Case study 1 is significantly heated and has charring depths of 30 mm in both directions (Figure 3 a).

The rock wool insulation shows far better results in the fire protection of the timber beam, in comparison to the Type X gypsum board. After one hour of fire exposure the cross-section of the beam in Case study 2 remains cold, that is not a case with the beam in Case study 3 which has a charring depth of 30 mm in the vertical direction (Figure 4 b and Figure 5 b). Figure 3 b shows that after one hour of fire exposure the unprotected beam has a highly reduced cross-section.

3.4. STRUCTURAL ANALYSIS

The timber beam protected with rock wool (Case study 2) has reached higher fire resistance (time to failure) in comparison to the timber beam protected with Type X gypsum boards (Case study 3). Both beams satisfy the required fire resistance of 60 minutes, but the beam in Case study 2 has by far favourable cross-section temperature distribution compared to the one in Case study 3 (Figure 4 b and Figure 5 b). The unprotected timber beam has a fire resistance of tf=37 min. Besides the benefit to the thermal distribution in the timber cross-section, the contribution of the rock wool to the structural fire performance of the beam is confirmed too. The cold cross-section in Case study 2 results with prolongation of the load-bearing resistance of the beam and smaller mid-span vertical displacements (Figure 7). The vertical mid-span displacements of the analysed beams (Δy) are presented in Table 2.

Table 2: Vertical displacements at mid-span of the beams, for different case studies

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

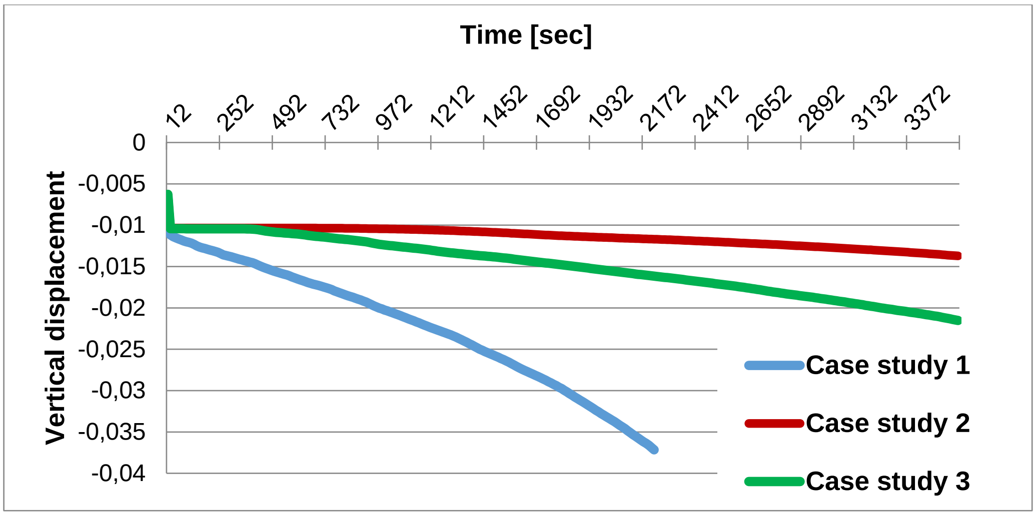

Figure 7: Time and temperature dependent vertical displacements at beams mid-span

4. CONCLUSIONS

The acceptable fire performance of unprotected timber elements should be attributed to the charring effect of the wood. The char layer acts as an insulator and protects the core of the wood section. For the required duration of fire exposure, unprotected beams may withstand the design loads only if proper dimensions of the cross-section are used. Fire exposed beams protected with gypsum fireboards at the bottom show improved fire resistance, but best results are achieved when the protection material from bottom side is rock wool. The improved fire resistance and the reduced deflections of the fire protected beams should be attributed to the positive effect of the insulation materials on the temperature distribution in the cross-sections of the beams.

In practice, if there are no architectural requirements for visibility of timber elements, floor and roof structures are constructed as in Case study 3 and the rock wool is used only for satisfying the energy efficiency requirements. The results obtained in this study show that a layer of rock wool from the bottom side of the structure (not only as an infill) will significantly improve the fire resistance of the whole structure.

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