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FIRE SAFETY OF ENERGY EFFICIENT BUILDINGS

Summary: *This paper presents the numerically achieved results for the fire resistance of several types of floor structures which are mostly used in our residential and rural buildings and in same time fulfill the energy efficient criteria, as: semi-prefabricated reinforced concrete slabs system FERT and STIRODOM (with infill of extruded polystyrene -XPS), timber-concrete composite floor structure and traditional timber floor structure. The solid RC slab was analyzed only for comparison. Using the computer programs SAFIR and FIRE, the effect of the intensity of the permanent and variable actions and the effect of the thermal isolation on the fire resistance of simply supported slabs were analyzed. The fire resistance was defined with respect to the criteria of usability of the structures in fire conditions, according to Eurocodes.*
Fire spread through the facades is widely recognized as one of the fastest pathways of fire spreading in the buildings. Numerical simulation of external fire on a facade was done. The fire resistance of RC wall, with and without thermal insulation, was defined and the negative effect of the extruded polystyrene, as external insulation, in comparison with the rock wool insulation is presented.
Key words: *energy efficiency, heat transfer, temperature, fire resistance, thermal isolation, floor structures, simply supported slabs, building fasades.*

POŽARNA BEZBEDNOST ENERGETSKI EFIKASNIH OBJEKATA

Rezime: *U radu su prikazani rezultati numeričke analize požarne otpornosti nekoliko tipova podnih konstrukcija koji se najćešće koriste u zgradama i u ruralnim kućama, a istovremeno zadovoljavaju kriterijume energetske efikasnosti. Takve konstrukcije su: polu-prefabrikovane armiranobetonske ploče system FERT I STIRODOM (sa ispunom od ekstrudiranog polistirena-XPS), kompozitna drvo-beton ploča i tradicionalna drvena podna konstrukcija. Za upoređenje analizirana je i klasična AB ploča. Primenom kompjuterskih programa SAFIR i FIRE analiziran je uticaj intenziteta početnog opterećenja i tipa izolacije na požarnu otpornost ovih slobodno oslonjenih ploča. Kriterijumi požarne otpornosti usvojeni su u skladu sa preporukama datim u Eurokodove.*
Širenje požara preko fasada je jedan od najbržih načina širenja požara na susedne požarne sektore i susedne objekte. U radu je prezentirana numerička simulacija dejstva spoljašnjeg požara na fasadi. Određena je požarna otpornost AB zida, sa i bez termičke izolacije, i potencirana je negativna strana ekstrudiranog polistirena u poređenju sa izolacijom od kamene vune.
Ključne reči: *energetska efikasnost, prenos toplote, temperatura, požarna otpornost, termička izolacija, podne konstrukcije, slobodno oslonjene ploče, fasade objekata.*

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1. INTRODUCTION

Nowadays the growing focus on “sustainable” buildings results in an increased thickness of building insulation and an extended use of combustible insulation materials e.g. foam plastics or cellulose fibers [4,5,7]. Moreover, it has become more common to apply the insulation to the external wall surface instead of in the wall cavity, and as part of the floor structure used for ceiling or floor over the unheated basements. The tendency to use thicker layers of insulation and a wider use of combustible insulation materials is identified to pose a potential risk to fire safety of buildings [4,5,7]. Controlling the fire spread in a building can increase the time available for occupant evacuation, decrease the fire losses and help the fire fighters in evacuating occupants and efficiently fighting the fire as well as increase the time available to reduce the fire spread to higher floors and adjacent buildings.

The fire resistance of structural elements is defined with respect to the criteria of usability of the structures in fire conditions, according to Eurocodes [2-3] and the standards in force. The criterion Integrity (E) expresses the ability of the separating element of the building construction, 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. The criterion Insulation (I) expresses the ability of the separating element of the building construction when exposed to fire on one side, to restrict the temperature rise of the unexposed face below specified levels and the criterion Load bearing function (R) expresses the ability of the structure or the member to sustain specified actions during the relevant fire, according to defined criteria. Criterion “I” may be assumed to be satisfied where the average temperature rise over the whole of the non-exposed surface is limited to 140 K, and the maximum temperature rise at any point of that surface does not exceed 180 K [2].

Floor structures, as horizontal elements, have a very important role in providing bearing capacity, usability and stability of the building as a whole. Their proper selection and design, when they are exposed to different types of loads (mainly: permanent and variable), should provide stable and safe structure during the exploitation period. In case of fire floor structures do not have only load bearing function. In most cases they are used as elements for separating the fire compartment. Where compartmentation is required, the elements forming the boundaries of the fire compartment, including joints, shall be designed and constructed in such a way that they maintain their separating function during the relevant fire exposure [2-3]. This shall ensure, where relevant, that integrity failure does not occur, insulation failure does not occur, thermal radiation from the unexposed side is limited. Does the floor structure meet the required fire resistance criteria mainly depends on: mechanical and thermal characteristics of the materials used for the construction; initial loading level; support conditions; dimensions of the cross section; steel ratio; concrete cover thickness and fire scenario.

In most European countries only a reaction to fire class of the façade constructions is required and the structural fire safety and fire resistance of the load bearing elements is not taken under consideration. The heat exposure from the diffusion gas burner used in the Single Burning Item (SBI) test is simulating a burning waste basket. Several studies have shown that results from the SBI test does not reflect how a building product will perform in a real fire, especially regarding the fire spread. In fact, when the SBI method was developed it was concluded that the method gives insufficiently reproducible results for most of the products. Especially for high rise buildings it is important to assess the complete construction of façade insulation systems, and not only the reaction to fire performance of the single components. In several EU countries a national large-scale façade test must be passed. Those tests are more realistic compared to the SBI test since heat exposure, size and spread of the flames in the large-scale tests are closer to the end-use condition.

In order to acknowledge the fire properties of a specific insulation product and give products with a low combustibility an advantage over products with a high combustibility, a more gradual approach is needed (i.e. combining combustible insulation materials with a protective layer). Based on the risk class of the building and the reaction to fire of the insulation product in use, an appropriate fire protection measure should be determined. For non-combustible insulation products no protective measures need to be specified. In that case, the reaction to fire performance for the construction as a whole is considered sufficient.

This paper presents the numerically achieved results for the fire resistance of few types of energy efficient floor structures, as timber-concrete composite floor structure TCCFS, traditional timber floor structure TFS, for two different fire scenarios, as well as of semi-prefabricated reinforced concrete slabs system FERT and STIRODOM (with infill of extruded polystyrene-XPS) exposed to ISO 834 standard fire from the bottom side. Fire resistance of reinforced concrete facade wall with different types of thermal insulation from the external side is defined too, and the results are presented.

2. FIRE RESISTANCE OF TIMBER BASED FLOOR STRUCTURES

The timber floor is widely used in traditional and rural buildings, but the high combustibility of the wood results in low fire resistance of this type of floors. Wood can be protected by fire protective claddings, other protection materials or by other structural members and nowadays a special attention is paid to this problem. One of the possible solutions for increasing the fire resistance of wooden floor structures is the composite timber-concrete floor assembly made of timber girders and reinforced concrete slab, while the cavities are field with mineral or rock wool.

The effect of the intensity of the permanent actions and the effect of the position of the ISO 834 standard fire on the fire resistance of the two types of simply supported floor structures were analyzed by using the software SAFIR [6], based on finite element method. The fire resistance was defined with respect to the load bearing criteria of the structure in fire conditions, according to EN 1995-1-2 [3].

The cross sections and the dimensions of the two different types of simply supported floor structures with span L=5m were defined according to the current standards and are presented on Figure 1. Material properties at room temperatures are given in Table 1. The temperature dependent physical and mechanical properties of the siliceous aggregate concrete (compressive strength f_c=30Mpa) and the reinforcement (yield strength f_y=400Mpa) were assumed according to EN 1992-1-2 [2]. For standard fire exposure, values of thermal conductivity, specific heat and the ratio of density of soft wood were taken as given in EN 1995-1-2. The thermal conductivity values of the char layer are apparent values rather than measured values of charcoal, in order to take into account increased heat transfer due to shrinkage cracks above 500°C and the consumption of the char layer at about 1000°C (Figure 2). Cracks in the charcoal increase heat transfer due to radiation and convection. The computer program SAFIR [6] does not take into account these effects.

Each type of floor structure was analyzed for two different types of ceiling: lime cement mortar 2cm or gypsum plasterboard 2cm, and for two different positions of the fire action, at the top and at the bottom side of the floor:

- 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 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.

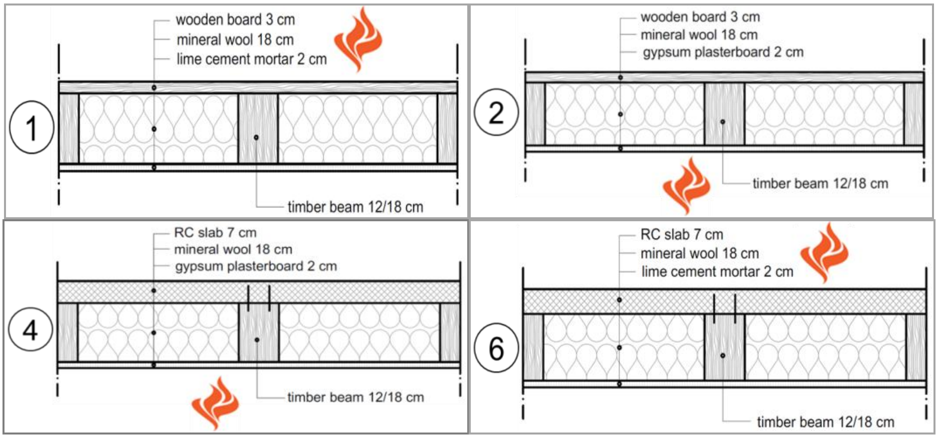

Figure 1. The cross sections and the dimensions of the two different types of simply supported floor structures with specified position of the fire action

Material properties	dimens.	Concrete	Wood	Gypsum	Mortar	Mineral 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^{2}K	25	25	25	25	25
convection coeff. on cold side	W/m^{2}K	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

* The values for the specific heat and the thermal conductivity of concrete and wood are temperature dependent and only the initial values are given (T=20^{o}C). Reductions of the values at higher temperatures are as it is recommended in EN 1992-1-2 and EN 1995-1-2.

Table 1. Material properties of composite materials at room temperatures

Numerically achieved results for the temperature distribution in the cross section of timber-concrete composite floor structure with gypsum plasterboard ceiling, for different position of the fire, are presented on Figure 3.

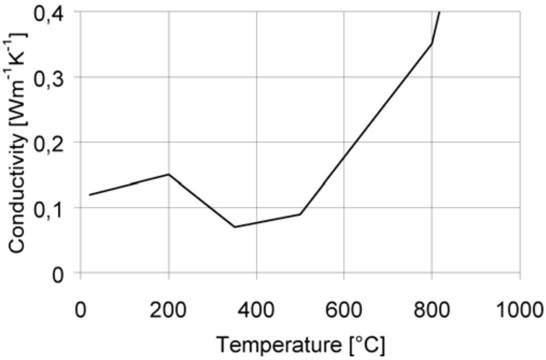

Figure 2. Temperature-thermal conductivity relationship for wood and the char layer, according to EN 1995-1-2

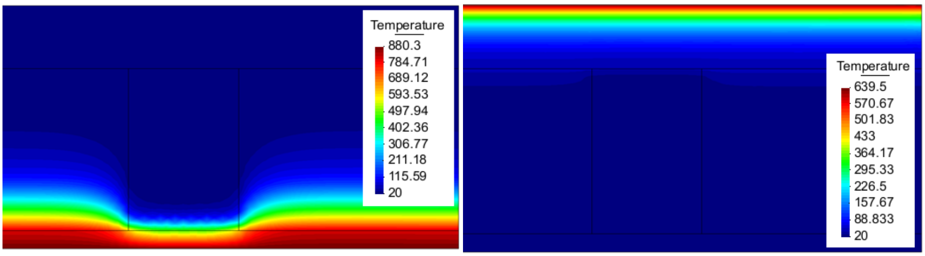

Figure 3. Temperature distribution in the cross section of timber-concrete composite floor structure with gypsum plasterboard ceiling, at the moment of failure (q_{fi}/q_u= 0.8)
a) case 4-fire from the bottom side, t=2410 sec.; b) case 6-fire from the top side, t=1080 sec.

Numerically achieved results for the fire resistance of the two types of floors, for all 6 cases and different load coefficients, are presented on Figure 4 and Figure 5.

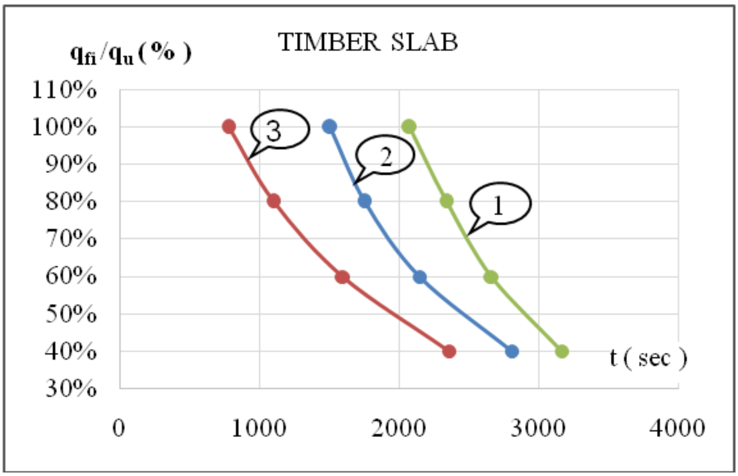

Figure 4. The effect of the intensity of the permanent action and the position of the ISO 834 standard fire on the fire resistance of the simply supported timber floor structure

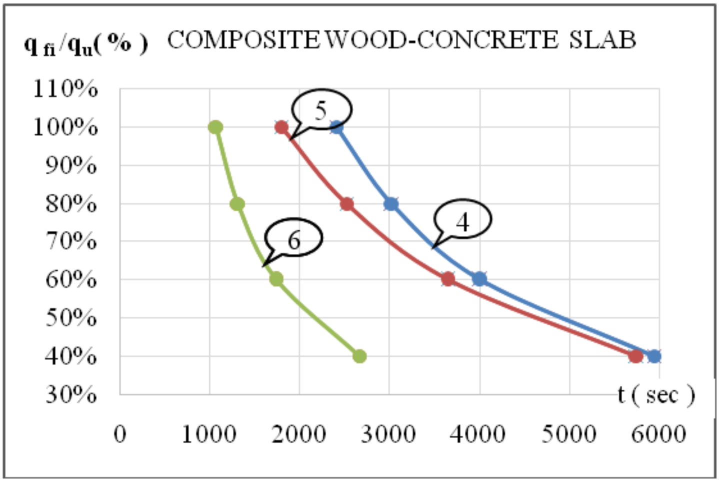

Figure 5. The effect of the intensity of the permanent action and the position of the ISO 834 standard fire on the fire resistance of simply supported wood-concrete composite floor structure

The analysis presented in this paper show that from all six cases, the timber-concrete composite floor structure with ceiling made of gypsum plasterboard and exposed to fire from the bottom side has the best performance. The gypsum plasterboard ceiling and the rock wool infill have an insulating function and provide lower temperatures in the cross section of the floor assembly (Figure 3a). When the fire is from the top side of the thin concrete slab (d=7cm), in short time period the temperature penetrates dipper into the concrete slab (Figure 3b), the slab loses the bearing capacity and becomes a dead load for the timber girder, therefore the whole structure collapses earlier than in previous case. The additional reason for the failure is the compression stress in the concrete slab caused by the non-uniform temperature distribution in the cross section. When the floor structure is exposed to fire from the top, the upper side of the concrete slab becomes hotter than the bottom side and tends to expand more. The free thermal expansion is restricted by the linear strain distribution in the cross section of the slab and results in additional compression in the concrete slab and tension in the timber beam. When the fire is from the bottom side of the floor structure the effect of the non-linear temperature gradient is opposite, the positive moment at the mid-span is decreased and this effect increases the fire resistance of the simply supported floor structure.

When the floor structure is without ceiling made of gypsum plasterboard and rock wool infill, the timber beam and the concrete slab are directly exposed to the flames, the temperatures in the cross section are higher than in other cases and the fire resistance has the lowest value (Figure 6).

When the load coefficient q_{fi}/q_u is increased (q_{fi} is the permanent action in fire condition and q_u is the ultimate load of the structure at ambient temperature), the fire resistance is decreased, but not proportionaly to the value of the load coefficient and this effect is mostly stressed in case 5. The timber floor structure (case 1, 2 and 3) has much lower fire resistance than the timber-concrete composite floor structure. It is more expressed when the load coefficient q_{fi}/q_u has expected values (less than 0.5). When fire is from the top side the char layer protects the timber girder from burning (low value of the thermal conductivity, Figure 2) and the girder keeps his original dimensions for a longer period than in case when the fire is from the bottom side.

For expected values of the load coefficient (q_{fi}/q_u less than 0.5) and for the same fire scenario, the fire resistance of the timber concrete composite floor structure is almost twice higher than the fire resistance of the timber floor structure.

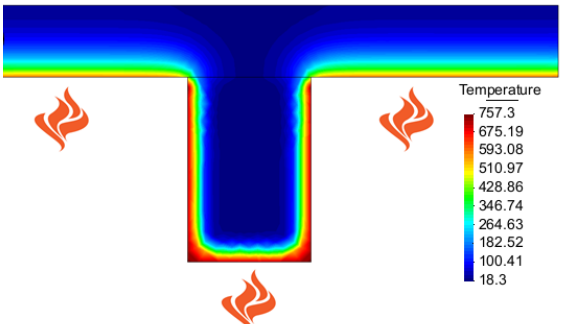

Figure 6. Temperature distribution in the cross section of timber-concrete composite floor structure without gypsum plasterboard ceiling, at the moment of failure (q_{fi}/q_u= 0.8), t=924 sec

3. FIRE RESISTANCE OF SEMI-PREFABRICATED FLOOR STRUCTURES

The fire resistance of three types of enrgy efficient floor structures that are mostly used in our buildings are analysed: semi-prefabricated reinforced concrete slabs system FERT and STIRODOM, as well as solid RC slab, for comparison (Figure 7). All three types of slabs were analysed as simply supported slabs L=6m and were exposed to ISO standard fire from the bottom side, as most critical fire scenario. The RC slabs and the slabs system STIRODOM were constructed with and without thermal insolation at the bottom side od the slabs and the positive effect of the thermal insulation was confirmed.

The computer programs SAFIR [6] (University of Liege, Belgium) and FIRE [1] (Cvetkovska, Ss. Cyril and Methodius University in Skopje, Macedonia), based on Finite Element Method, were used for the fire resistance analysis. Both programs are capable of conducting the nonlinear and transient heat flow analysis and nonlinear stress-strain response associated with fire.

The temperature dependent physical and mechanical properties of the siliceous aggregate concrete (compressive strength fc=30Mpa) and the reinforcement (yield strength fy=400Mpa) were assumed according to EC2, part 1-2. Phusical properties of other materials at ambient temperature were taken according to the values provided by the producers and are given in Table 2.

Properties/material		brick	Plasterboard	EPS	Concrete	Reinforcement
density	kg/m^3	1500	1000	30	2400	7800
thermal conductivity	W/mK	0.80	0.21	0.035	2.0	54
specific heat	J/kgK	920	1090	1450	960	440
Surface emissivity		0.93	0.85	0.90	0.92	0.69

Table 2. Material properties of composite materials at room temperatures

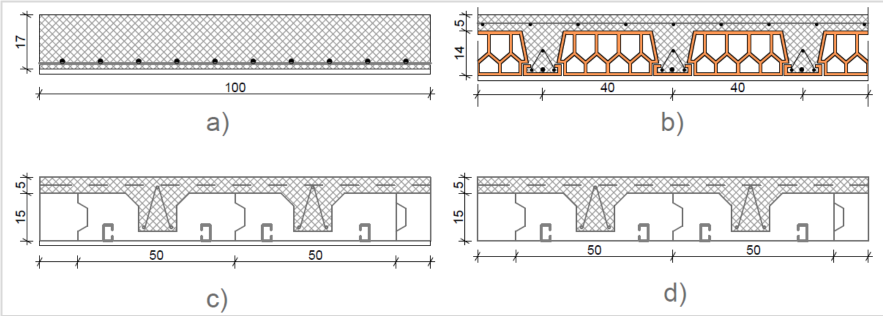

Figure 7. Different types of floor structures: a) RC slab; b) slab system FERT; c) slab system STIRODOM with plasterboard as thermal insulation; d) slab system STIRODOM

As first case study the criterion **Load bearing function (R)** was analyzed. For all types of floor structures the design loads (permanent and variable) at ambient temperatures were assumed to be the loads that cause vertical deformation equal to L/250 [2]. These loads were considerably lower than the ultimate loads. For the selected types of floor structures the fire resistance in time domain is presented in Figure 8.

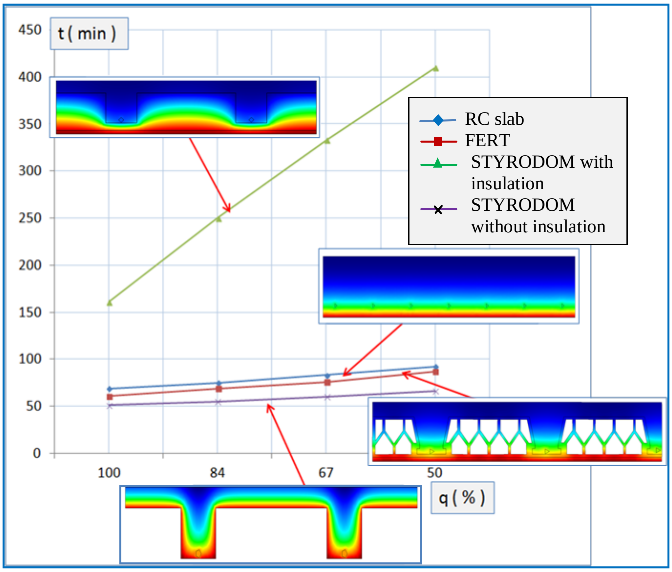

Figure 8. Fire resistance of different types of simply supported floor structures, as function of the applied loads expressed as percentage of the design loads that cause deflections L/250

The design loads that at ambient temperatures cause vertical deformation equal to L/250 are taken as 100%. All other loads are given as a percentage of these limited design loads (84%, 67% and 50%). Differences in the fire resistance of the certain types of floor structures are not significant except for the slab system STYRODOM with ceiling of plasterboard. This type of floor structure is more resistant to the effects of temperature and the fire resistance is much higher than for the other types of floor structures. The same structure, but without plasterboard at the bottom (ceiling) side (only thin plaster layer), has the lowest fire resistance. The reason for that is the melting of the infill of extruded polystyrene-XPS caused by temperatures over T=240°C. At temperatures T=450-500°C the infill is completely burned and the temperatures in the cross section of the slab are much higher than in other three cases. Consequently, the deflection rapidly increases much more over the limited value L/30.

As a second case study the **Insulation criterion (I)** was analysed. For fulfillment of this criterion the average temperature rise over the whole of the non-exposed surface was limited to 140°C, that means the temperature was limited to 160°C (the ambient temperature before action of fire was 20°C) and the maximum temperature at any point of that surface was limited to 200°C. In case of slab system STYRODOM without plasterboard at the bottom side the temperatures in the cross section were highest (Figure 9). The reason for that was the melting of the infill of extruded polystyrene-XPS caused by temperatures over T=240°C. The speed of melting was 4-6,4 mm/sec. In case when thermal insulation of 1.5cm plasterboard was applied at the bottom side of the slab, the moment of melting was posponed and temperatures of the cross sectin were less then in case without plasterboard (Figure 10).

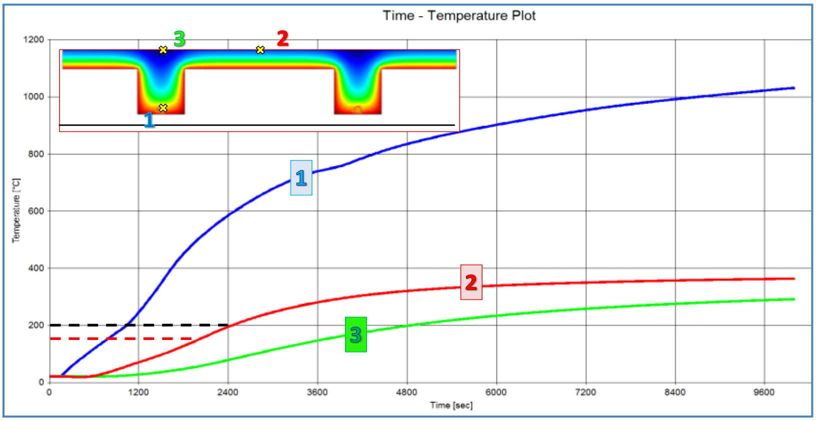

Figure 9. Temperatures in characteristic points of the cross section of slab system STYRODOM without plasterboard at the bottom side

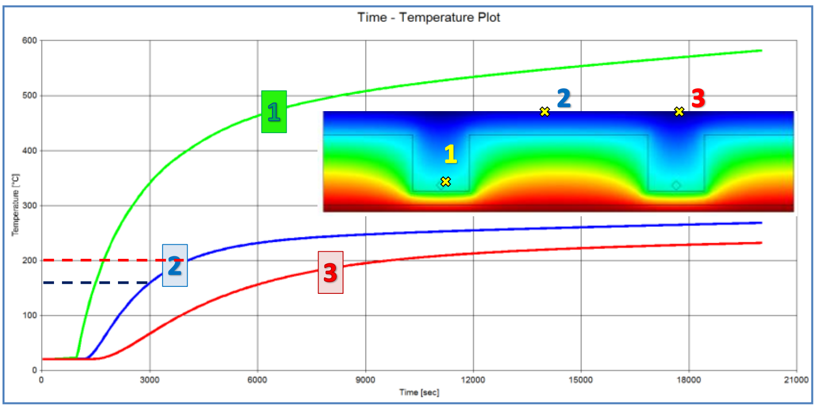

Figure 10. Temperatures in characteristic points of the cross section of slab system STYRODOM with plasterboard as thermal insulation at the bottom side

The analysis show that from all three types of floor structures the RC slabs have the best performance at ambient temperature, as well as in case of fire. The performance of the slab system FERT when exposed to fire is satisfactory too, but we should not neglect its lower stiffness and greater deflections at ambient temperatures. The fire resistance of the contemporary floor structures (STYRODOM, ITONG, etc.) depends on the thermal insulation of the slab. The infill of extruded polystyrene-XPS is sensitive on temperatures over 240°C, therefore we should no avoid these structures, but it is necessary to provide protective measures.

4. FIRE RESISTANCE OF ENERGY EFFICIEN EXTERIOR RC WALL

Fire spread through the facades is widely recognized as one of the fastest pathways of fire spreading in the buildings. The fire spread on a facade is influenced by both the location of the initial fire and its intensity. Actual fires as well as several fire tests have shown that a fire inside a building with a flashover has the most detrimental effect on the facade. The Flames reach lengths up to 5 m. The length of the flames depends on the fire load, the size and the geometry of the windows. They generally reach heights of two floors above the fire source, given a conventional height of the floors. The general safety goals are to ensure the load bearing capacity of the building over a defined duration, to avoid spread of fire to other buildings or fire compartments, to ensure the escape or the rescue of inhabitants and the safety of the rescue team.

Many combustible materials are used today in commercial wall assemblies to improve energy performance, reduce water and air infiltration, and allow for aesthetic design flexibility. One of these materials is the extruded polystyrene. The polystyrene is thermoplastic material which is temperature unstable. At 85-90°C shrinkage is activated, at 240-250°C melting process starts and at 280-290°C toxic gases are released. Because of these characteristics, whenever the polystyrene is used as insulation in the building façade, special measures have to be undertaken for improvement of the fire safety of the whole building.

Numerical simulation of external fire on a facade was done. The fire resistance of RC wall, with and without thermal insulation, was defined and the negative effect of the extruded polystyrene, as external insulation, in comparison with the rock wool insulation is recognized. The wall thickness was d=16cm. The siliceous aggregate concrete strength was f_c=30Mpa. The reinforcement ϕ12/12.5cm (RA400/500) was used on both sides and the concrete cover thickness was 3cm (for the longitudinal reinforcement). The load coefficient was 0.3 (the axial force at ambient temperature caused compression stresses 9.0 Mpa). Material properties of composite materials at room temperatures are given in Table 1 and Table 2. Three different cases were analyzed:

1. RC wall without any insulation, ISO 834 standard fire from inside and external fire curve [1] from outside;
2. RC wall with 2 cm mortar from inside and 5cm extruded polystyrene from outside, ISO 834 standard fire from inside and external fire curve from outside;
3. RC wall with 2 cm mortar from inside and 5cm mineral wool from outside, ISO 834 standard fire from inside and external fire curve from outside.

In case of RC wall without insulation the lowest fire resistance is achieved. At moment t=2.68 hours the RC wall failed in compression. The second case, with 2 cm mortar from inside and 5cm extruded polystyrene from outside, has much higher fire resistance t=5.0 hours, but after 18 minutes of external fire exposure the melting process started and this process is always followed by relies of toxic gases (Figure 11). After half an hour 2 cm of the thermal insulation is melted and after 1 hour almost the whole extruded polystyrene is melted and the temperature penetrates deep into the cross section (Figure 12).

Figure 11. Toxic gases released from the burning façade made of EPS

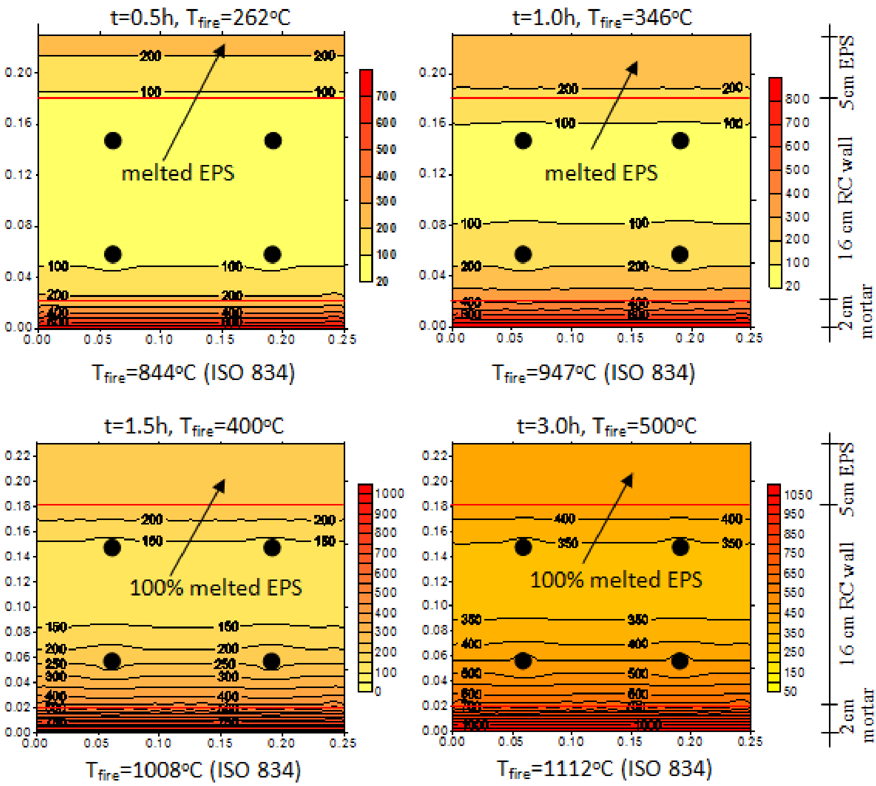

Figure 12. Time redistribution of temperatures in the cross section of RC wall with thermal insulation of extruded polysyrene, exposed to fire from both sides

If mineral wool is used insteade of EPS (case 3), the thermal insulation stays stable even on temperatures higher than 600°C and there are no toxic gases. The temperatures in the cross section of the RC wall are lowest (Figure 13), concequently the fire resistance is highest and is t=6.55 hours.

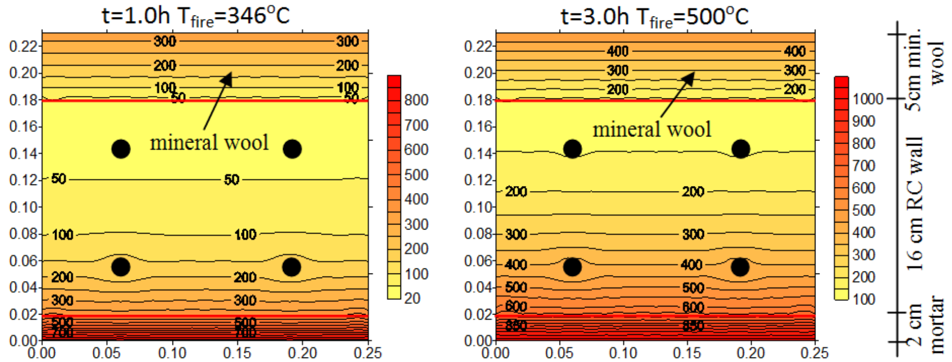

Figure 13. Time redistribution of temperatures in the cross section of RC wall with thermal insulation of mineral wool, exposed to fire from both sides

The testing method according the British standard BS 8414 is used for ETICS systems to prove their fire resistance and this test has revealed that façade fires can in fact spread very rapidly depending on the type of materials used. The advantage of the facade made of extruded or expanded polystyrene (ETICS facade) is that significantly reduces thermal transmission through outer walls and therefore helps to reduce the heating and cooling costs by 50% or more. This facade also greatly improves the living comfort – both in hot and cold climates. But the negative side is that the extensive use of combustible insulation materials in ETICS without proper fire protections and barriers were believed to contribute to the uncontrollable fire spread in the high-rise buildings.

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