5.1. Fire design in Europe

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5.1.1 INTRODUCTION

European countries have started applying Eurocodes to fire design. In the past they used to have separate structural and fire codes, which are now integrated into a single standard system. Earlier, let's say, fire loads and mechanical loads were defined in different sources, but now both are in given in the EN 1991 series.

Performance based fire design was created long ago but is still a new concept in many countries. In Sweden and UK, the countries that have most experience from it, local authorities still have a great influence on which solutions are approved locally especially as concerns fire design.

Performance based design is frequently used to design the evacuation and exit routes of buildings and to estimate smoke and toxin propagation. Due to the huge improvements in methods, computing facilities and know-how of engineers, performance based design can now be used to estimate temperatures in fire compartments and load bearing structures. That allows calculating the resistance of structures in fire.

The developments in fire design have led to close co-operation between authorities, clients, architects and fire safety, mechanical and structural engineers in actual projects. Co-operation is always important, and performance based design intensifies it in projects. It results in better fire safety of buildings, because the fire scenarios and related risks have to be analysed carefully when using performance based fire design.

This study shows the situation with respect to fire Eurocodes and performance based design in 10 European countries presently. A case study that promotes the design of load bearing structures ex-posed to fire is also included. The fire scenarios and corresponding design fire packages for a large sports centre built in Helsinki, Finland are presented as well as the results of the fire simulations.

5.1.2 EUROPEAN RULES

5.1.2.1 *Scope of the study*

European countries are starting to apply the EN standards for buildings. They include principles and application rules for fire resistance design of buildings which also allow performance based fire design. What is the situation with respect to applying the EN standards for fire resistance design and, especially, performance based design? What kinds of applications of performance based fire design do we have experiences from? These were the main questions to which we sought answers from members of the COST C26 during spring 2008. A short summary of the results follows. The questions and further details can be found in Heinisuo (2009). Answers were received from ten countries (three from UK). Table 5.1.1 shows the introduction of EN standards and the countries which answered the questions.

Table 5.1.1. Introduction of fire ENs in ten European countries.

	1991-1-2	1992-1-2	1993-1-2	1994-1-2	1995-1-2	1996-1-2	1999-1-2
Belgium	2008	2008	2008	2008	2008	2008	2008
Czech Republic	2006	2006	2006	2006	2006	2006	2008
Finland	2007	2007	2007	2007	2007	2008	2008
France							
Hungary	2005	2005	2005	2005	2005	2005	2007
Italy	2008	2008	2008	2008	2008	2008	
Poland	2006	2008	2007	2008	2008	2009	2010
Portugal	2008	2008	2008	2008	2008	2008	2008
Romania	2007	2008	2007	2007	2007	2008	2008
UK	2002	2004	2005	2005	2004	2005	2007

5.1.2.2 *Annexes to EN 1991-1-2*

The national fire codes of Czech Republic, UK, Finland, Hungary, and Italy cover performance based design. It can be used in Belgium if an exception to the Fire Regulations is approved by the Minister of the Interior. France allows its partial application with respect to fire resistance and smoke propagation design. UK has used performance based fire design the longest.

When the ENs are used for fire design, the essential data for performing calculations is found in the Annexes of Standard EN 1991-1-2 (2002). EN 1991-1-2 has seven annexes (A-G). All the annexes are informative only, meaning that any country can substitute them by their own rules, or restrict their use.

The ten countries accept Annexes B (thermal actions for external members – simplified calculation method) and G (configuration factor) as they are. To the others, they have made some modifications.

Two countries (Belgium, France) allow using Annex A (parametric temperature-time curves) only in the preliminary design stage. In France the use of Annexes C (localised fire) and D (advanced fire models) requires a peer review. Use of Annex E (fire load densities) and Annex C is subject to restrictions. E.g. Finland only allows using Chapter E.4. In France Annex E is banned entirely. Five countries (Belgium, Finland, France, Portugal, and UK) do not allow use of Annex F that deals with equivalent time of fire exposure. In UK almost all the annexes have been substituted by the national PD 6688-1-2:2007 standard.

The detailed question dealt with the National Annex for EN 1991-1-2, clause 4.3.1(2) dealing with the representative values of variable actions in fire. Both combination factors, ψ_1 and ψ_2, are used in Europe. This means that, for example, the snow load in fire is defined differently in various parts of Europe.

In Italy and Romania ψ_2 is used for variable actions in fire. France and Portugal (and Spain, Estonia, Slovenia according to the DIFISEK+ project) use ψ_1. In UK ψ_2 is used for EQU cases and ψ_2 for STR cases. Belgium (and Netherlands and Luxembourg according to the DIFISEK + project) uses ψ_2, except for wind when it uses ψ_1. The Czech Republic uses ψ_2, except for wind and snow where the choice is ψ_1. Finland uses ψ_2 for live loads and ψ_1 for wind, snow and ice actions.

5.1.2.3 *Current projects*

Performance based fire design has been used in real projects in 8 countries, 10 of which answered the query. Performance based fire design has been used to:

- determine the fire resistance of structures,
- perform evacuation calculations,
- perform smoke control,
- perform risk analyses,
- optimise the fire protection of structures,
- study local fires,
- study external flames,
- study equivalent times of exposures,
- demonstrate adequacy of fire fighting provisions,

– demonstrate functioning of escape routes,
– demonstrate the existence of an acceptable standard of safety for complex buildings with large numbers of people and/or large open spaces.

There are many examples of different kinds of applications of performance based fire design in Europe. Typically performance based fire design has been used in large projects, but it is now gaining ground also in smaller ones. Typical projects using it include:
– shopping centres,
– office buildings,
– airports,
– hospitals,
– residential buildings,
– stadiums,
– music halls,
– underground facilities,
– industrial buildings,
– historical buildings,
– high rise buildings,
– car parks,
– libraries,
– churches,
– monumental buildings,
– warehouses.

One interesting project involved a cruiser.

When performance based fire design is used, approval of the design by the third party may or may not be required. Typically no specific qualification is required of the fire designer, but many countries may require some proof of competence in the future. E.g. Finland grants certificates to skilled fire safety and structural engineers, and authorities frequently require their participation in projects where performance based fire design is used. Requirements for the documentation of fire design are set by 50 % of the countries.

The main problems related to performance based fire design are: lack of experience and confidence of authorities, definition of design fires and parameters in some cases, and lack of design tools. Heinisuo (2009) lists the software used in fire design of:
– fire simulations,
– evacuation simulations and
– resistance checks of members.

Some ideas about the level of education of fire design engineers were gleaned from the answers. Generally the education of fire engineers seems to be of a very low level in the 10 countries involved. In Czech Republic, France and Poland some improvements are planned. Sweden is a country where sector education is first rate.

5.1.3 CASE STUDY

5.1.3.1 *Salmisaari Sports Centre*

Salmisaari Sports Centre is located in the middle of Helsinki, Finland. The building will be ready for use in April 2010. The floor area of the building is 22,200 m^2 and its volume 167,700 m^3. The main contractor is YIT Rakennus Oy. The architects and consulting structural and fire engineers are Arkkitehtitoimisto Pekka Lukkaroinen Oy and Finnmap Consulting Oy and L2 Paloturvallisuus Oy, respectively. The load bearing structures were delivered by Ruukki Construction Oy.

The length, width and height of the building are about 136, 35 and 36 metres. There are four stories, each 8-10 metres high. Each storey has a space about 30 m wide supported by 30 m span trusses located at every 5 metres. These trusses are innovative structures used in some Finnish projects: the top chord is made of a welded slim floor box beam that supports pre-stressed hollow core concrete slabs, the braces are of tubular steel and the bottom chord is a flat steel bar.

The trusses are about 3 m high. That leaves a lot of space for installations below the floors. The columns supporting the trusses are reinforced concrete filled steel tubes. A general view and the space examined in this study are shown in Figure 5.1.1.

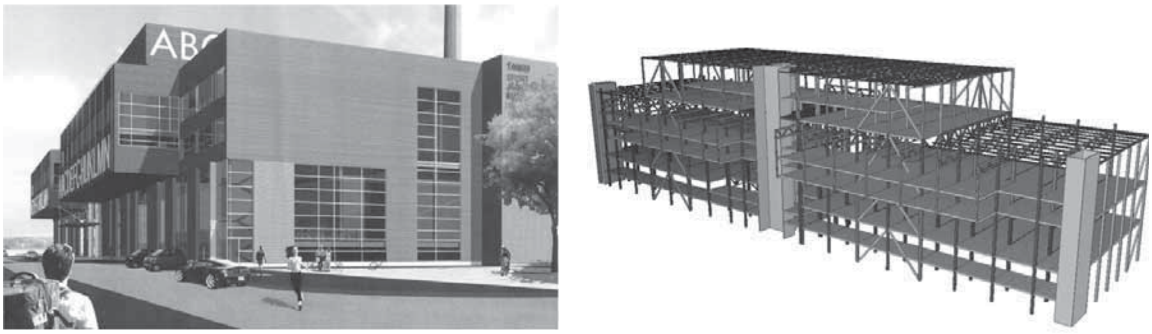


Figure 5.1.1. General view and the examined space.

Performance based fire design was applied in this project only to trusses. Fire actions were determined for the parts of the building topped by trusses. The intended uses of the spaces below the trusses are:

– First floor: two ice hockey rinks (total area 4200 m^2).
– Second floor: Bowling, martial arts and restaurants (2000 m^2).
– Third floor: Adventure place for children (2000 m2), beach volley (780 m^2) and badminton (570 m^2).
– Fourth floor: dancing (900 m^2).
– Climbing wall, area 170 m^2, and max. height 30 m.

Fire actions were determined for the intended uses of the spaces, and for the following special cases:

– Ice resurfacing machine fire,
– Storage fire with flashover,
– Coat-rack fire,
– Plastic slide fire,
– Stage fire (abnormal use),
– Stand fire (abnormal use),
– Climbing equipment fire.

The fire safety plan was prepared by the fire engineers of the project. Fire compartments were partitioned using EI60 structures. The fire compartments consist of stairwells, exit areas, storage spaces, offices, saunas, dressing rooms and special facilities. According to the safety plan, the building should have the following fire safety equipment:

– Initial extinguishing equipment, consisting of: one portable extinguisher per 300 m^2 or hose reels.
– Automatic alarm system covering the whole building.
– Smoke extraction, mainly by the fire brigade.
– Automatic sprinkler system.

According to CEA (1998) requirements, the sprinkler system should be able to detect and put out a fire in its early stage, or to restrict the spread of fire until the fire brigade arrives.

Fire actions are determined based on fires which may occur in different spaces (during intended use, special use and abnormal use). The effects of the sprinkler system are taken into account when defining design fires. Traditionally the effects of the actions of the fire brigade and other fire fighting measures are not taken into account in defining design fires. Fire brigade actions are taken into account in the following references: Tillander et al. (2009), Karhula & Hietaniemi (2008), NFPA (1996), Barry (2002) and Hietaniemi (2008).

A summary of the definitions of design fires used in the performance based fire design of this project is given below. More details are given in a report by Hietaniemi (2009). In Finland it is not possible to use Annex E.1 of EN 1991-1-2 (not applicable) to define the fire activation risk due to the size of the compartment and the type of occupancy, which is why probability analysis was used in this study. Fire load densities were determined based on national fire load classifications of occupancies and by conducting a fire load survey using both analysis and synthesis of experimental data as well as modelling and fire simulation.

The fire scenarios and all details of the fire load calculations were approved by the local authorities, the client and the fire safety and structural engineers of the project before fire simulations and structural calculations were done.

5.1.3.2 *Fire actions based on intended uses of spaces*

The following properties are supposed to be valid for the sprinklers:
- RTI = 110 $m^{1/2}$ $s^{1/2}$
- Activation temperature is 67 °C
- Protection area A_r of one sprinkler is 12 m^2.

The defect frequency of sprinklers is 3 % according to International Fire Engineering Guidelines (2005). Assuming a floor area of 5000 m2, and a 12 m2 protection area, about 500 sprinklers are required on that floor. Then the probability is that one of those sprinkler heads is defective. Let us then suppose that this defective sprinkler head is just above the starting point of the fire. The resulting fire scenario would be a so-called local fire in the sprinklered building where:
- The other sprinklers restrict the fire to the protection area of one sprinkler.
- Fire intensity is defined by the use of the space under consideration, as shown later.

Let us then consider the failure of the entire sprinkler system. That can be estimated by the defect flow of Figure 5.1.2. The sources of the initial data are the following:
- Pump defect, Isaksson et al. (1998),
- Duct defect and water source defect, Isaksson et al. (1998),
- Installation defect, Korpela (2002).

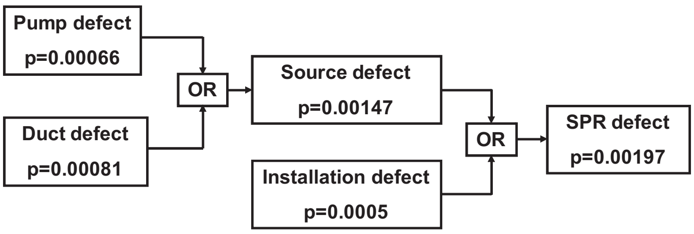


Figure 5.1.2. Defect flow of sprinklers.

The probability for failure of the entire sprinkler system is about 0.00197 ≈ 0.2 % according to the estimate. On that basis a second fire scenario is created involving a so-called global fire in the sprinklered building:
- After sprinkler activation the fire intensity is doubled from the value defined based on the use of the space at sprinkler activation time and it remains constant. The doubling pro-vides the extra safety required by authorities in this case.

So we end up with two fire scenarios, the first one based on local sprinkler defects and the second one on the failure of the entire sprinkler system. They are graphically demonstrated in Figure 5.1.3. In the first case the fire decays either due to a lack of oxygen or combustible material in the space. The fire is local within an area of 12 m2 and should be applied to the most severe locations in the building. The second fire is not dying down and engulfs the whole floor under consideration.

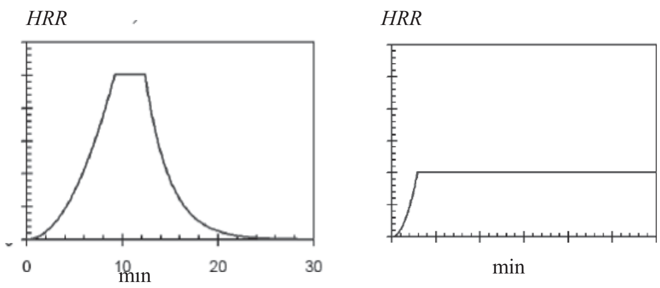


Figure 5.1.3. Schematic fire loads (heat release rates, *HRR* in MW), local (left) and global (right) fires.

The local and global fires in a sprinklered building defined above were assumed to occur at the most severe locations in the building.

The special uses, including abnormal uses, and corresponding fires were also assumed to occur in the building. The probabilities of these fire activations resulting from the size of the compartments and the occupancies are given in Table 5.1.2. The probabilities were calculated based on Tillander et al. (2009) for a 50 year period. Probabilities for abnormal uses were calculated assuming their occurrence once a month.

The probabilities for local and global fires are given in Hietaniemi (2009).

Table 5.1.2. Probability of fire activations and sprinkler defects during 50 years of special uses of spaces.

	First floor		Second floor	Third floor		Fourth floor
	Ice machine	Storage	Coat-rack	Plastic slide	Stand (abnormal)	Stage (abnormal)
A_r (m^2)	4200	45	12	2000	260	900
A_r/A_{tot}	0.221	0.002	0.0006	0.10	0.013	0.047
Fire activation	6.8 E-01	1.2 E-02	3.2 E-03	4.2 E-01	5.8 E-03	2.0 E-02
Sprinkler defect	3.3 E-02	3.6 E-04	9.7 E-05	1.6 E-02	1.7 E-04	6.0 E-04

Next we shall consider the fire load intensities q'' [MJ/m^2] for local and global fires. These can be estimated based on local regulations and experimental data.

Finnish regulations (Ympäristöministeriö (2002)) state that the value for stores should be more than 1200 MJ/m^2. For shops, exhibitions halls and libraries its proper range is 600-1200 MJ/m^2. For restaurants, smaller than 300 m^2 shops, offices, schools, sports halls, theatres, churches, and similar buildings the value is below 600 MJ/m^2. Based on the above, the maximum value for sporting areas is 600 MJ/m^2.

Measured data (International Fire Engineering Guidelines (2005)) yielded 421 fire load intensities for production spaces, which are clearly higher than in our cases. The mean of the sample was 530 MJ/m^2 and the deviation 540 MJ/m^2. The 3-parameter gamma distribution was used with the following results: 80 % fractile = 600 MJ/m^2 and 95 % fractile = 1100 MJ/m^2, see Figure 5.1.4.

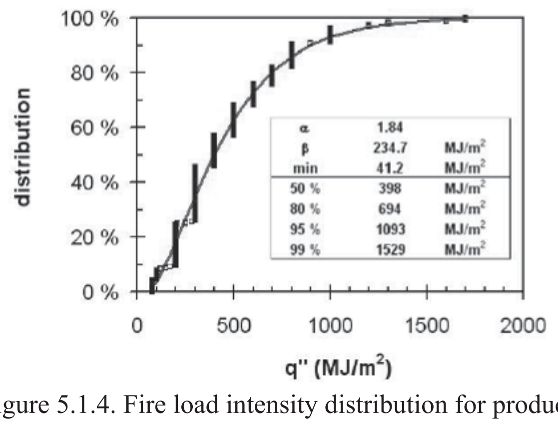


Figure 5.1.4. Fire load intensity distribution for production space.

Based on these estimations, the following fire load intensities were used in this study:

- 600 MJ/m^2 for the spaces meant for sporting (80 % fractile for generic fire intensity distribution).
- 1100 MJ/m^2 for other spaces excluding stores (95 % fractile for generic fire load intensity distribution).

Next we shall consider the corresponding fire release rates (*HRRPUA*, Heat Release Rate Per Unit Area). Table 5.1.3 draws on data from Hietaniemi (2007). It presents the fire load intensities and corresponding fire release rates. The origin of each data line is given in Hietaniemi (2007).

Table 5.1.3. Sample of *HRRPUA* and *q''* values.

Item	t_g [s]	HRRPUA [kW/m^2]	q'' [MJ/m^2]
Wood pile (4 pieces)	209-409	469-2156	703-1561
Stack of pallets (2 pieces)	600-900	3062-4105	1500-2250
One plastic chair	900	600	160
Stack of plastic chairs	110	7600	1140
Two stacks of plastic chairs	110	4300	1450
Sports bags	420	1324	1829
Fair stand	150	1966	1203
Litter basket (2 pieces)	140-1450	1200-1400	400-422
Carton	150	1966	1230
Work point in office (8 pieces)	115-225	820-1799	376-914
Television		930	500
Washing machine	273	1422	639
Washing machine in cabinet	563	1483	1054
Refrigerator	660	1921	1031
Polyester coat	720	250	40
Coat-rack (2 pieces)	150-210	188-190	90-125
Shoe store	80	2500	1760
Speciality shop	71	2900	2900
Armchair	120	5480	980
Sofa (2 pieces)	110-110	3120-3375	727-940
Unprotected mattress	145	527	126
Protected mattress	360	34	3

The close correlation between fire load intensity and heat release rate per unit area is shown by Figure 5.1.5.

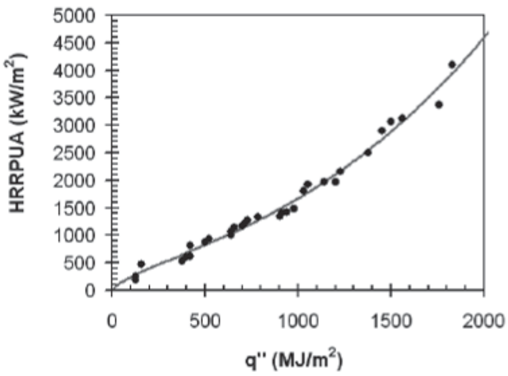


Figure 5.1.5. *HRRPUA* versus fire load intensity.

Thus, fire release rates can be estimated based on fire load intensities:

- For sporting areas the mean fire release rate is 1000 kW/m^2 and its 5 % and 95 % fractiles are 800 kW/m^2 and 1100 kW/m^2 (see Figure 5.1.6 a)).
- For other spaces (excluding stores) it is 1900 kW/m^2 and its 5 % and 95 % fractiles are 1600 kW/m^2 and 2100 kW/m^2 (see Figure 5.1.6 b)).

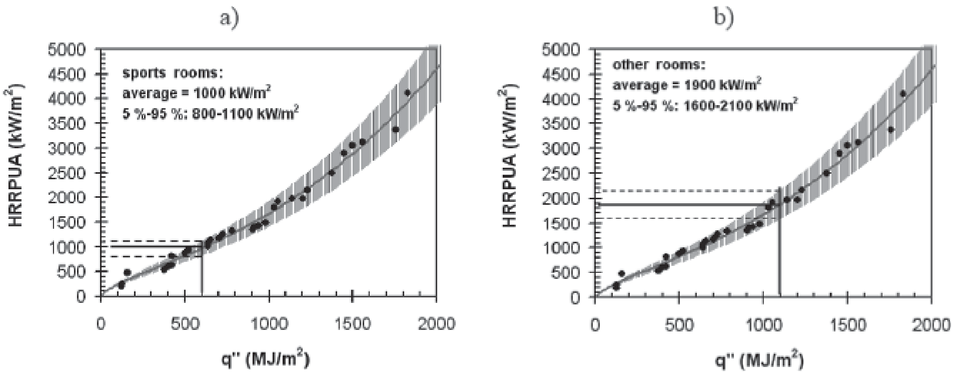


Figure 5.1.6. *HRRPUA* for two types of spaces, shading indicates values between 5 % and 95 % fractiles.

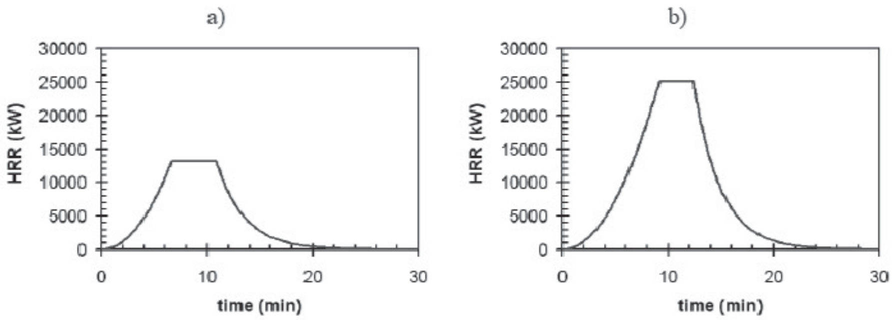
Next, we fit the local fire ($A_r = 12$ m^2) curve of Figure 5.1.3 to the data above. In the growing phase we use the t^2 curve including the time t_g needed to reach a heat release rate of 1 MW. In the decay phase we use an exponential curve including a creeping factor of 30 % of total heat release based on experimental values. Fire intensity is:

The height H_f of the fire source can be estimated using the equation 1.

$$Q(t) = \begin{cases} Q_0 \cdot \left(\dfrac{t}{t_g} \right)^2 & when \quad 0 \le t \le t_1 \quad (growing\ phase) \\ Q_{\max} & when \quad t_1 < t \le t_2 \\ Q_{\max} \cdot \exp(-\dfrac{t - t_2}{\tau}) & when \quad t > t_2 \quad (decay\ phase) \end{cases} \tag{1}$$

where $Q_0 = 1$ MW, $t_g = 150$ s, τ is the creeping factor and t_1 and t_2 are the limit times for uniform fire intensity.

The result for the sports area is shown in Figure 5.1.7 a) and for other areas in Figure 5.1.7 b). The maximum *HRR* for the sports area is little below 15 MW and for other spaces little over 25 MW.



fire area A_f =	12	m^2
HRRPUA =	1100	kW/m^2
q'' =	600	MJ/m^2
max HRR =	13200	kW
Q =	7200	MJ
t_g =	110	s
t_1 =	400	s
t_2 =	650	s
τ =	160	s

fire area A_f =	12	m^2
HRRPUA =	2100	kW/m^2
q'' =	1100	MJ/m^2
max HRR =	25200	kW
Q =	13200	MJ
t_g =	110	s
t_1 =	552	s
t_2 =	740	s
τ =	155	s

Figure 5.1.7. Local design fires and their parameters.

The *HRR* for the corresponding global fire is shown in Figure 5.1.8.

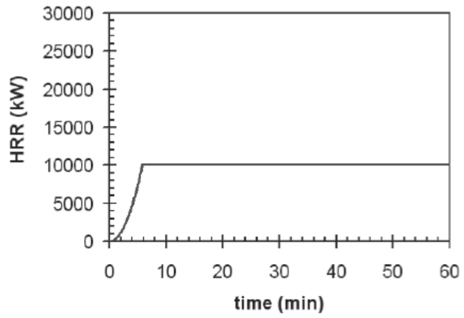


Figure 5.1.8. Global design fire.

In studying structures above the fire, the simplified geometrical model for modelling the local fire uses a square (3 x 4 = 12 m^2) at a specific height from the floor, and the fire burns only on the top surface. Special cases where the fire source was supposed to be 5 m above the floor were considered too.

The height H_f of the fire source can be estimated using the equation 5.1.2.

$$H_f = \frac{q''}{\eta \cdot \Delta H_c \cdot \rho_{fuel}} \tag{5.1.2}$$

where q'' is the fire load intensity, ΔH_c is the calorific value of the material (supposed to be within 25-44 MJ/kg), η is the factor that accounts for the solidity of the material (one for a solid material, zero for a loose material) and ρ_{fuel} is the density of the material (supposed to be within 900-1200 kg/m^3).

IF we suppose for simplicity uniform distribution of all the quantities within the ranges shown above and a 10-90 % range for the factor η. Then, based on 1000 Monte-Carlo simulations we find that for 600 MJ/m^2 the value H_f is smaller than about 20 cm (Figure 5.1.9 a) and for 1100 MJ/m^2 the value H_f is smaller than about 50 cm (Figure 5.1.9 b).

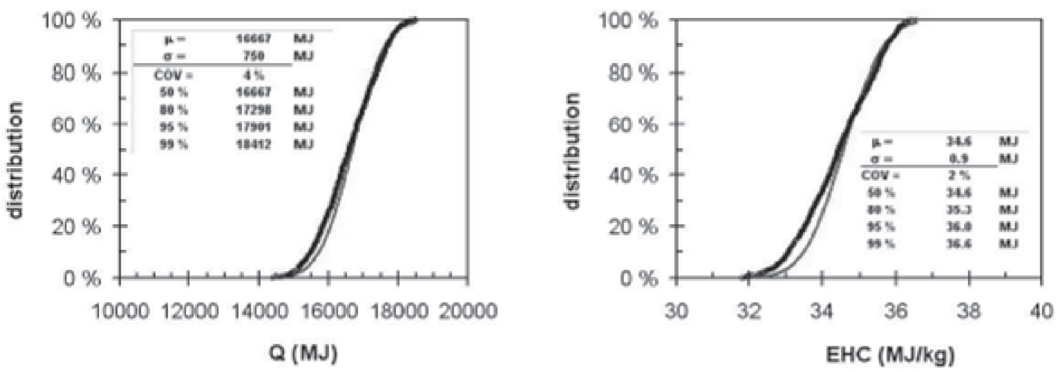


Figure 5.1.9. Distributions for the burning item.

Traditionally the value H_f = 0.5 m is used for both cases. The fire source area used in the simulations is shown in Figure 5.1.10.

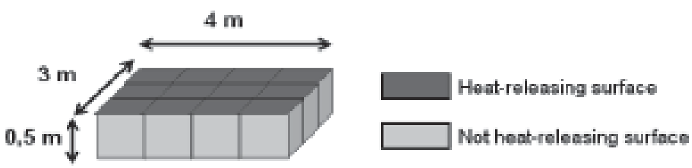


Figure 5.1.10. Geometrical model for burning item (local fire).

Next, we shall consider the design fires for special uses.

5.1.3.3 *Ice resurfacing machine fire*

Two kinds of approaches were used to define the design fire for this case: simulation with the FDS 5 program and estimation with a general fire model for vehicles (Hietaniemi 2007). The goal was to define the design fire for the ICECAT (2008) machine shown in Figure 5.1.11.

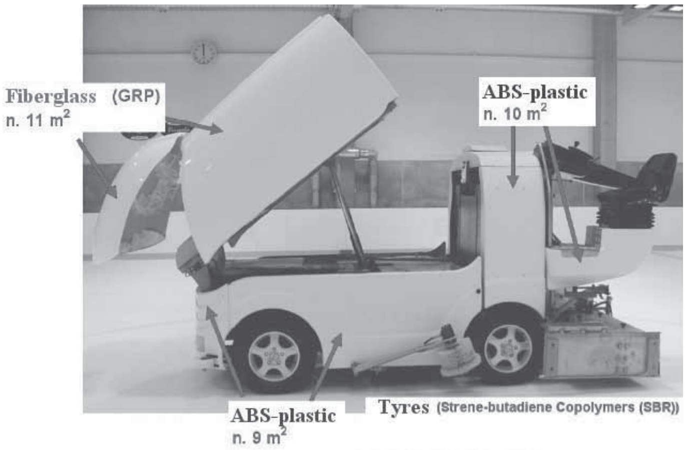


Figure 5.1.11. Ice resurfacing machine.

The machine contains the following combustible materials: plastics (ABS), glass-reinforced plastic (GRP) and rubber. The properties of ABS were derived from Lyon & Walters (2001) and Scudamore et al. (1991), those of GRP from Mouritz & Mathys (2006) and those of rubber from Iqbal et al. (2004), Chapter 7.

The machine was modelled with FDS 5 using cubes fit to the grid size and amount, distances, total size and mass of the cubes fit to the machine data. The FDS 5 model is shown in Figure 5.1.12.

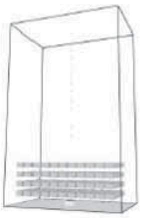


Figure 5.1.12. FDS 5 model for predicting the fire load of ice resurfacing machine.

The thermal properties used in the simulation were typical for plastics: density 1100 kg/m^3, thermal conductivity 0.2 WK^{-1}m^{-1} and specific heat 1500 JK^{-1}kg^{-1}. Combustion time is estimated at 30 s and combustion temperature at 320 $^{\circ}$C. The fire is supposed to reach its maximum intensity in 60 s.

The simulation is based on normal distributed fire load [*Q*, MJ], effective net caloric value [*EHC*, MJ/kg] and heat release rate per unit area [*HRRPUA*, kW/m^2]. Their distributions are shown in Figure 5.1.13.

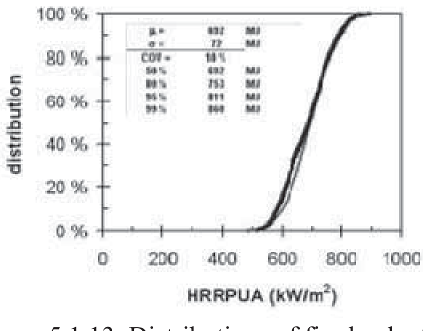


Figure 5.1.13. Distributions of fire load, effective net caloric value and HRRPUA.

In the simulations the following 95 % fractiles were used as input. Their standard deviations are shown in parentheses:

- Q: 16700 (750) MJ,
- *EHC*: 35 (1) MJ/kg,
- *HRRPUA*: 700 (70) kW/m^2.

In some cases other fractiles were used to determine the effect of the input on the result. The result of the simulation is shown in Figure 5.1.14.

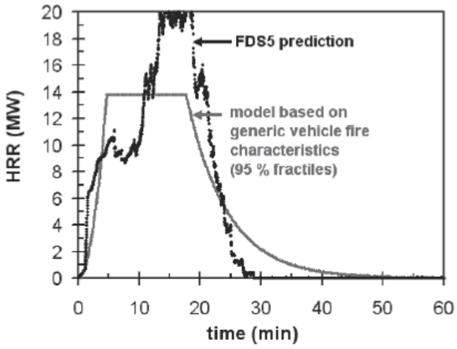


Figure. 14. FDS 5 prediction and general vehicle model prediction for the ice resurfacing machine fire.

Figure 5.1.14 also shows the result based on Hietaniemi (2007) using the 95 % fractiles 2225 MJ/m^2 for the fire load and 1725 kW/m^2 for the heat release rate.

The final design fires for the ice resurfacing machine were determined based on these analyses. They are presented in Figure 5.1.15. Figure 5.1.15 a) presents the local fire and Figure 5.1.15 b) the global fire where after the total collapse of the sprinkler system the heat release rate doubles and then remains constant.

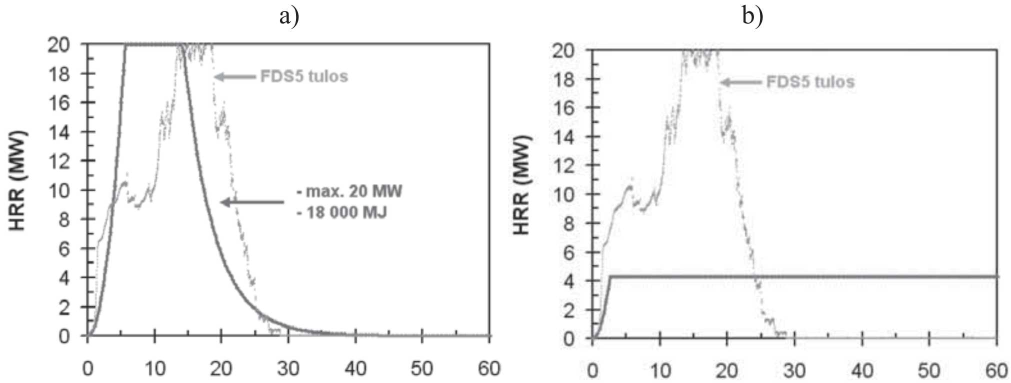


Figure. 15. Local and global ice machine design fires. Vertical axis shows time in minutes.

5.1.3.4 *Storage fire with flashover*

The large compartment comprises storage spaces which should be divided into individual compartments using EI60 structures. However, the doors of the spaces open into the large compartment which is why the scenario where the door is open during the fire was chosen.

The storage space was modelled as a single sprinklered floor area because that represents the most severe situation as flames come out of the storage door. The fire load was modelled using 64 burning units each equalling a cell of the FDS grid. The heat release rate from each surface of each unit was 500 kW/m^2. The net caloric value was 35 MJ/kg and the total fire load 30,000 MJ. The FDS 5 model and an example of the flaming through the door are presented in Figure 5.1.16.

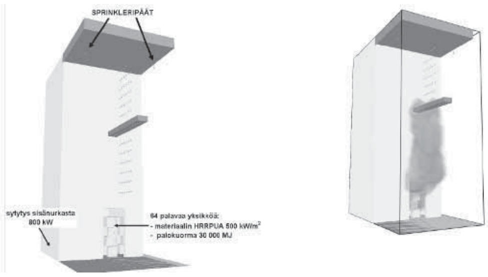


Figure 5.1.16. FDS 5 model for predicting the storage fire load and an example of flaming through the door.

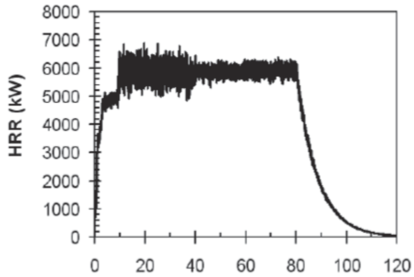


Figure 5.1.17. Design fire for storage with flashover. Time in minutes.

5.1.3.5 *Coat-rack fire with local flashover*

The definition of the design fire for this case started by modifying the FDS 5 model to simulate closely the experiments of Hadjisophocleous & Zalok (2004). The HRRPUA was 160 kW/m2 and the EHC was 30 MJ/kg. The geometrical model, the FDS 5 model and examples of the fire are presented in Figure 5.1.18.

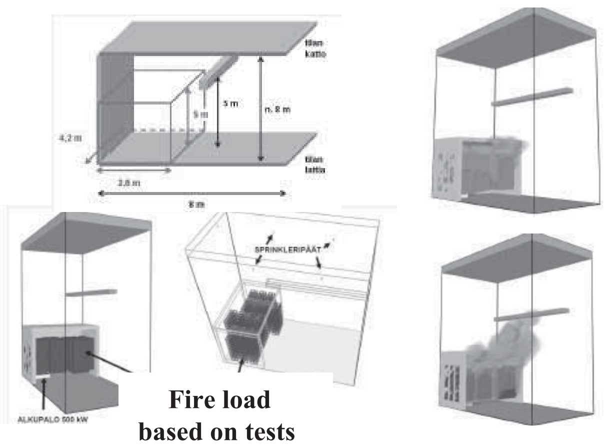


Figure 5.1.18. Geometrical model, FDS 5 model and examples of fires to predict the coat-rack fire.

The fire loads for the basic case and two variations are presented in Figure 5.1.19. The first variation is calculated using double the *HRRPUA* [kW/m^2] value of the basic case. The second variation is calculated using double the fire load intensity [MJ/m^2] of the basic case.

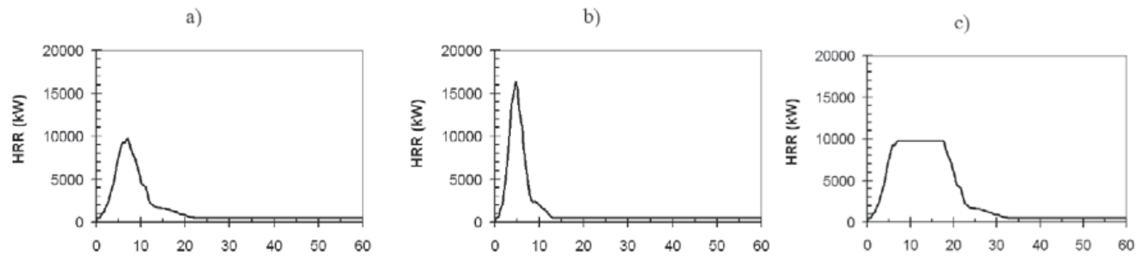


Figure 5.1.19. The basic case (a) and two variations: doubled heat release rate (b), and doubled fire load intensity (c).

The fire of Figure 5.1.19 c) was used in the final simulations of the building fires.

5.1.3.6 Plastic slide fire

The most hazardous object in the adventure space for children in case of fire is the plastic slide which is high and contains a lot of combustible materials. The slide and its simplified model are presented in Figure 5.1.20.

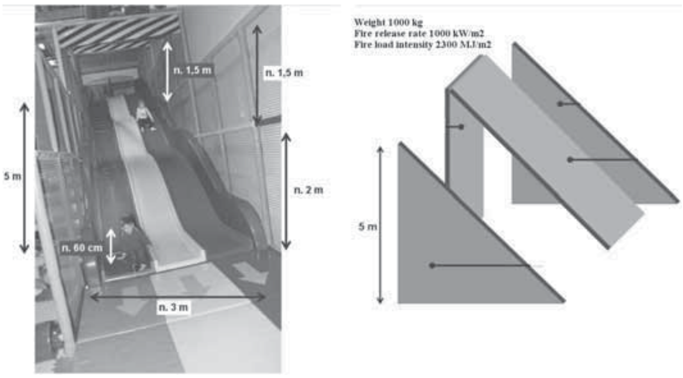


Figure 5.1.20. Plastic slide and its simplified geometrical model.

More refined models of parts of the slide are presented in Figure 5.1.21.

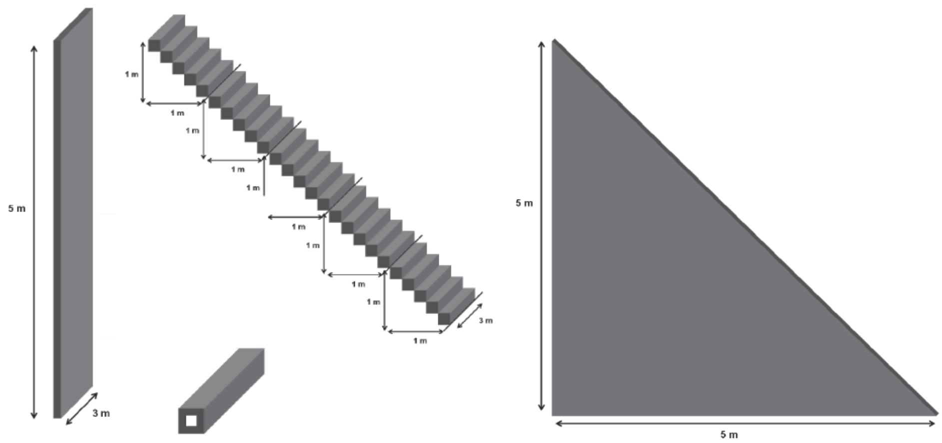


Figure 5.1.21. Description of slide and related quantity data.

Two possible ignition locations were considered as shown in Figure 5.1.22 a). The corresponding fires are presented in Figure 5.1.22 b).

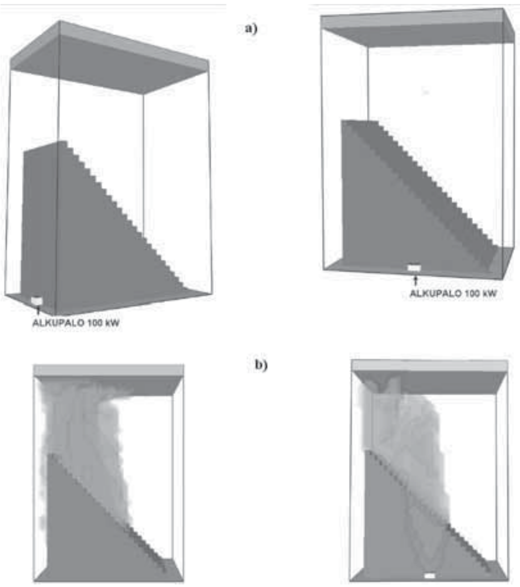


Figure 5.1.22. Two ignition locations (a) and corresponding fires (b) for predicting the slide fire.

The corresponding design fires are presented in Figure 5.1.23 a) and b).

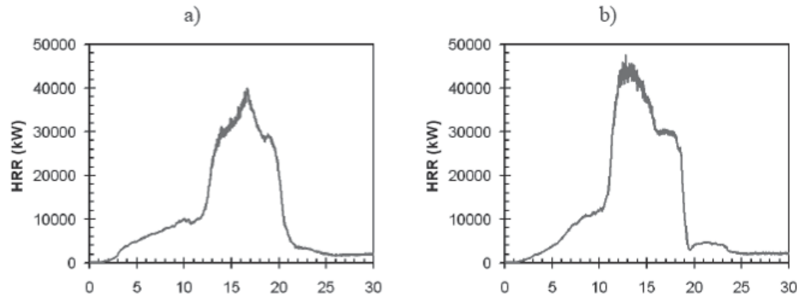


Figure 5.1.23. Local design fires for plastic slide with two ignition locations.

The design fire presented in Figure 5.1.24 was used for global fire.

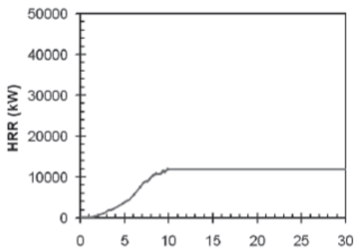


Figure 5.1.24. Global design fire for plastic slide, time in min.

The design fire used in this case was much larger than the doubled fire load after sprinkler activation (about 5 minutes in Figure 5.1.24.).

5.1.3.7 *Stage fire*

The stage is not a permanent structure and is not normally in use. However, it may be needed in the dance, which is why this scenario was also considered. Stage load was defined for the area of one sprinkler (12 m^2). The geometrical representation of the stage and the quantity data for calculating the fire load are given in Figure 5.1.25.

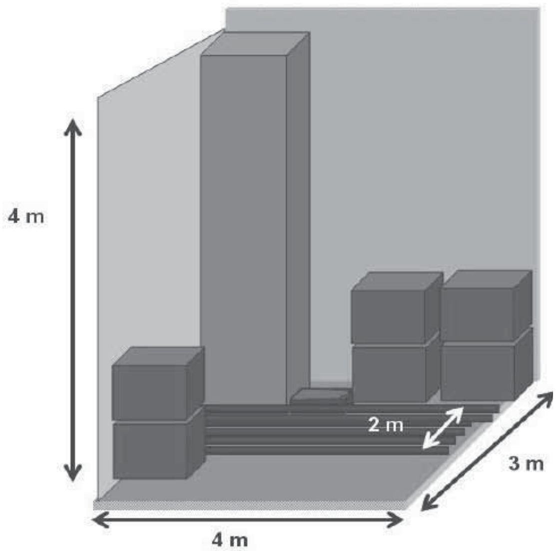


Figure 5.1.25. Stage model.

The quantity data and the corresponding fire are shown in Table. 4.

Table 5.1.4. Quantity data of stage fire.

	Density [kg/m^3]	Heating value [MJ/kg]	HRR [kW/m^2]	V [m^3]	A [m^2]	Weight [kg]	Fire load [MJ]
Speaker	200	30	1000	0.96	8.24	192	5780
Amplifiers	200	30	1000	0.86	8.40	173	5184
Cables	1200	40	450	0.72	60.84	144	5760
Platform	700	15	1000	0.30	12.35	60	900
Back wall	700	15	1000	0.40	16.40	80	1200
Curtain	1200	40	1000	0.01	12.01	2	96
Total							18900

The attributes of the single homogeneously burning stage material for the whole area are:

- HRRPUA = 1000.0 kW/m^2
- THICKNESS = 0.05 m
- DENSITY = 1200.0 kg/m^3
- HEAT_OF_COMBUSTION = 30.0 MJ/kg

The fire load of the stage is presented in Figure 5.1.25 with the fire load of a global fire (red line).

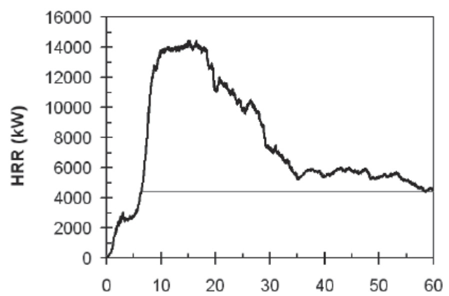


Figure 5.1.25. Stage design fire loads, local and global (red).

5.1.3.8 *Stand fire*

The stand is not a permanent structure. Temporary stands are needed for spectators of beach volley and badminton matches. The stand is made of plywood and plastics. Its geometrical model is given in Figure 5.1.26.

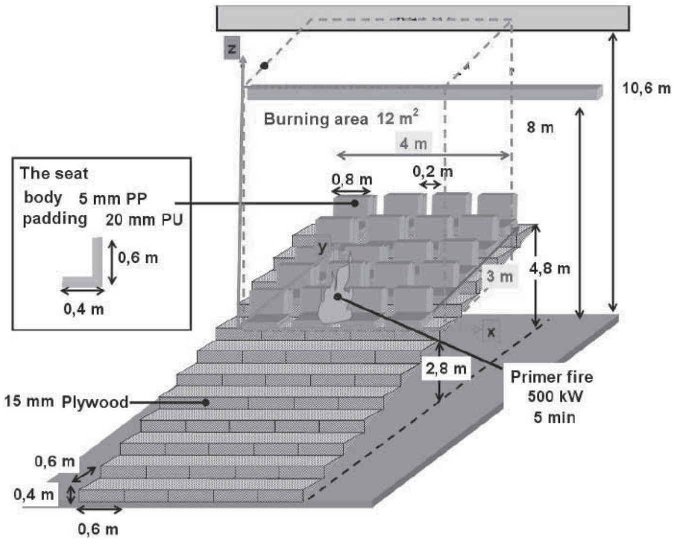


Figure 5.1.26. Geometrical fire model of the stand.

The quantity data and corresponding fire load calculations are shown in Table 5.1.5.

Table 5.1.5. Quantity data of one seat in the stand.

	Density [kg/m^3]	Heat value [MJ/kg]	HRR [kW/m^2]	V [m^3]	A [m^2]	Weight [kg]	Fire load [MJ]
Plywood	700	15	150	0.0072	0.72	5.04	75.6
PP	1200	40	1200	0.0024	0.72	2.88	115.2
PU	100	25	400	0.0096	0.72	0.96	24.0
Total							214.8

The size of the burning area is 12 m2. The attributes of the single homogeneously burning stand material are:

– HRRPUA = 583.0 kW/m^2
– THICKNESS = 0.2 m
– DENSITY = 52.0 kg/m^3
– HEAT_OF_COMBUSTION = 24.2 MJ/kg

Local and global design fires for this case are given in Figure 5.1.27.

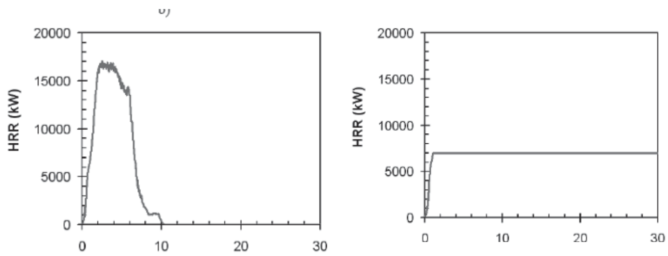


Figure 5.1.27. Local and global design fires for the. Time in minutes.

An example of a fire in the stand is given in Figure 5.1.28.

Figure 5.1.28. Stand fire.

5.1.4 *Estimation of errors*

Some error estimations concerning the proposed de-sign fires should be done before any fire simulations on the building. The selected fire scenarios meet the requirements of Finnish regulations (Ympäristöministeriö (2002), Chapter 1.3.2) and, thus, cover all fires that probably could take place in the building. They do not represent the average situation, but a rare situation which can be considered to represent 99 % of the cases. This means that one fire out of 100 can be worse than expected. That is a very small number, which means that in this study the possible uncertainty of the fire scenarios will be attributed to the uncertainty of the design fires.

The uncertainty of design fires consists of the uncertainty of our knowledge and our ignorance (epistemic and aleatoric uncertainty) such as:

- The values used in calculations, e.g. *HRRPUA* values, always include noise originating from non-ideal tests arrangements, measurements and analysis models.
- Possible systematic errors in the values used in calculations originating e.g. from the hypotheses made to simulate the real situation.

The uncertainty of fire technical measurements is of the order of 20 % as are model uncertainties. Assuming that systematic uncertainties are of the same order (20 %), the uncertainty $\Delta\dot{Q}$ of the fire load can be calculated by the equation 3.

$$\Delta\dot{Q} \approx \sqrt{20\%^2 + 20\%^2 + 20\%^2} \approx 34\% = \pm 17\% \tag{3}$$

According to fire plume models, gas temperature T_g rises in proportion to ambient temperature to the power 2/3 as shown by Heskestad (1984) and Hostikka (1997).

$$T_g \propto \dot{Q}^{2/3} \tag{4}$$

so the uncertainty ΔT_g of the temperature rise is

$$\Delta T_g \propto \frac{2}{3}\dot{Q} \tag{5}$$

This means that the relative uncertainty of the estimations of temperatures can be described as a normal distribution with a mean of 1 and a standard deviation of 10 %:

$$\frac{\Delta T_g}{T_g} \propto N(1;10\%) \tag{6}$$

5.1.5 FIRE SIMULATIONS

5.1.5.1 *The simulation environment*

The aim of the simulation was to estimate endurance of structures to natural fire. The structural product model was used as the basis of simulation. Beams, columns, roof and floor slabs, and concrete stairwells were incorporated in the model. The data content of the structures of that model was more complete than that of the architectural model. The building parts were not assumed to be involved the fire since all the burning material was assumed to be included in the fire packages. The material properties of structures were not needed in fire simulation.

The structural model was complemented based on drawings. The airspace where the fire burned was bounded by slabs or wall panels. All doors were modelled as openings in the walls assuming that evacuated persons had left them open. Other vents were for the most part not modelled. If there were any openings, the airspace where the fire burned could also be modelled by the properties of the edge of the calculation grid. The used modelling program was Tekla Structures version 15.0.

The NIST Fire Dynamics Simulator (FDS) version 5.2.5 was used for simulation. The calculation method is based on CFD (computational fluid dynamics) which uses a three- dimensional, rectilinear computation grid. All the modelled objects must be modified into cubes in some phase of the data transformation process.

A special data transformation program was used to transfer the structural model data to the FDS input file. At the same time, all needed material data were stored to the same input file. The process is described more accurately by Laasonen (2010).

5.1.5.2 *Selection of the grid cell size*

The size of a single cell of the calculation grid affects the following three important factors given in order of importance: 1) the reliability of simulation, 2) the minimum size of the objects that can be incorporate in the fire model, and 3) the computer time needed for calculations.

Heinisuo et al. (2008a) have discussed the required cell size. Heskestads's correlation is used to estimate the reliability of calculation. It uses the density of fire [kW/m^2] and the burning area to calculate the so-called Resolution factor (R) for defining the sizes of cells. Heinisuo et al. (2008a) recommended that the sizes of cells should be selected so that the value of R is at least 10 (or inverse value r not more than 0.07).

As presented in the previous chapters, the used special fires are not planar but involve three-dimensional objects which may burn on many faces. Then, the acceptable limit for the Resolution factor is not known. Two Resolution factors have been calculated based on simulated fires: a lower value when only the fire on the top face is included in the burning area, and the higher value when all the burning faces are included in the area.

To limit calculation time, the model was divided into the several grids. A calculation environment where every grid can be calculated by a different processor was used. However, the hottest area was not divided between several grids because that could cause problems to the stability of calculation. Also, if a larger number of processors are needed, the starting of calculations could be severely delayed.

Coarser grids were used for the colder parts. Alpert's correlation was used to approximate the width of the hot area. A distance from the plume centreline where the temperature should be less than 100 ˚C was calculated. This distance is always smaller than the distance to the edge of the coarse grid.

In the simulation environment the co-ordinates of modelled objects were not changed in the transformation to the fire simulation program. The simulation program was allowed to locate every co-ordinate to the nearest cell corner using normal mathematical rounding rules. If all the corners of an object are rounded to the same cell corner, it will vanish from the fire simulation. Because of rounding, the thickness of some objects may be zero. As long as the rounding cause any unwanted holes in the simulation model, it should not affect the calculation. The simulation program reads the real thickness of objects from their attributes.

The effect of rounding was observed by two methods. In the simulation environment the calculation grids were also added to the structural model. At least one edge of the grid could be located according to modelled structures. All the added geometry could also be located to the grid cells. For example, holes less than two cells in size were not used.

The other method involved visual checking of the fire simulation model. The checking was carefully done before calculation when most of the problems could been noticed. After calculation, smoke animation could indicate unwanted air flows.

To minimise calculation time, the biggest possible cell size was usually selected. Then the rounding of co-ordinates may cause structures to be lost in the fire simulation model. Profiles whose both dimensions are less than the cell size will probably be lost if not successfully located between cell corners. Profiles exactly the size of a cell can be lost if the cell corner is located exactly in the middle of the profile. That is highly improbable.

Heinisuo et al. (2008a) have tested the effect of different sizes of obstacles in a fire model. They noticed that if the obstacle height versus corridor height is below 0.1 in a ceilinged space, and the obstacles are not located close to each other (less than three times their height), it is not essential to model them in a fire simulation. Consequently, slender profiles do not change substantially the flow of air. The height of the modelled spaces was typically between 4 and 10 metres. Then it can be assumed that ignoring of obstacles smaller than 400 mm has little effect on simulation.

In the hot area the upper limit of cell size was 200 mm. Outside the hot area, the flow of air is even slower and bigger obstacles can be ignored in the fire model. There the upper limit of the cell size was 400 mm. The end result of the investigation of the effects of rounding was that profiles smaller than the cell size could be freely rounded off. The pictures of the fires in Chapter 5.5 show that, for example, all diagonal members of trusses have vanished from the fire models.

5.1.5.3 *Modelling of fires and grids*

The previously presented fire packages were used in simulations. The properties and behaviour of burning materials were converted to FDS language. The HRRPUA, CONDUCTIVITY, SPECIFIC_HEAT, HEAT_OF_COMBUSTION and DENSITY values were given. The slope depicting the development of the fire as a function of time was given. The material data of the fire were linked to the model so that the name of the FDS fire was included in the name of the geometrical object describing the fire.

The fire was modelled in the form of cubic geometry which follows the cells of the calculation grid. The location of the fire was selected for maximal temperatures of structures. Then the flames should reach the structure or just underneath. The other rule was that there should be enough air for the fire since the area around the opening is the severest.

The finest grid was located around the fire. One edge of the grid was aligned with the bearing structures. The exact location of the fire was fine-tuned accordingly. Then the other fine grids where located around the first one. Finally, the rest of the model was filled by coarser grids.

5.1.5.4 *Output of temperatures*

Air temperatures were output at certain points during fire simulation. The location of the points must be entered by co-ordinates to the input file of fire simulation. The middle point of every steel member was selected as a control point. That allowed reading the co-ordinates automatically from the structural model. Temperatures at different locations of long and vertical rods varied sometimes. The safe solution in such instances is to assign critical members the highest calculated temperature of the surroundings. In some cases extra control points above the fire were also included in the calculation.

The air flow near the flames and plumes is turbulent. The programs can simulate this when output temperatures vary a lot between successive calculation steps. In an intense fire the difference could be about 100 °C. If we wish to know the temperature at one point at a certain time, it is not advisable to take a single value from the time-temperature curve because of the turbulence. It is better to use the so-called ‘sliding window’ with the mean of several successive calculation steps.

One simulated second may involve several steps of calculations. That would make the amount of output data huge. The temperature of structures corresponds closely to the temperature of air. For these reasons, all the calculated steps are not used in post processing. Hostikka et al (2001) have presented an equation to calculate the width of the sliding window. In the output diagrams of simulations they reduced air temperatures to 10 seconds wide time steps. That value was considered suitable in all cases.

The temperature of a steel part can be calculated by integration from the time-temperature curve of air. Heinisuo et al. (2008b), among others, have presented examples of such calculations.

In the following, only the air temperature curves are given. These temperatures were used by the structural engineers of the project to check the resistance of the structures in fire.

5.1.5.5 *Simulated cases*

The calculations of the fire cases presented in Chapter 3 were done to determine the worst-case scenarios. The cases involving the highest temperatures are presented in the following. Results are presented mainly for those control points where air temperatures were over 400 °C. That is a critical limit because the yield stress of steel decreases at temperatures above it.

Table 5.1.6 lists the documented cases. The Resolution factor (R) is output as told in Chapter 5.2. An exception is the coat-rack fire where the relative area of the top faces was very small and the top of the coat-rack was closed as shown in Figure 5.1.32. The R value of the top faces in the coat-rack fire has not been output. All calculated values are at least near the minimum target value 10. The worst R value was calculated for the storage fire, but there only the top faces of the fire elements were burning.

The number of grids of both used cell sizes is given. The total number of grids of the fire models was between 7 and 16.

Table 5.1.6. Documented simulations.

	Resolution factor R		Number of grids		
	Burning faces		Size of cells [mm]		Σ
	top	all	200	400	
Ice hall, ice machine	9.6	13.9	3	6	9
Ice hall, storages	9.2	-	4	6	10
Restaurant, coat-rack	-	11.4	4	5	9
Fun park, slide	13.9	30.6	6	10	16
Dance hall, stage	13	23.8	6	2	8
Volleyball hall, stand	10.4	12.8	7	0	7
Climbing hall, climbing wall	13.4	25.6	8	0	8

The initial simulation time was one hour. In cases where the combustible material burned away, the simulation was stopped earlier. The output temperatures should have settled down before the stopping.

Table 5.1.7 shows the calculation times of simulations. The maximum numbers of cells in one grid and simulation time were output to compare different cases. As stated earlier, it is advisable to avoid dividing the grids around the fire to keep calculation times short. A long, intense fire also lengthens the calculation time in addition to the wideness of the grids.

Table 5.1.7. The simulation and the calculation times.

	Maximum number of cells of grids	Simulation time [min]	Calculation time of simulation [hh:mm]
Ice hall, ice machine	109824	33	33:47
Ice hall, storages	109824	60	41:02
Restaurant, coat-rack	100000	60	33:51
Fun park, slide	83200	60	41:01
Dance hall, stage	72000	50	86:13
Volleyball hall, stand	52000	25	16:33
Climbing hall, climbing wall	190256	23	55:28

The ice hall was modelled in actual size bounded by the designed walls. The space was so large that the fire qualities of the walls did not matter in the simulation. The fire was situated near a door so as to provide enough air. The burning part of the machine was at the actual level.

Figure 5.1.29 is an example of the visualisation of simulation. The door openings are white and the green points indicate where temperatures were output. Only a few bottom flanges of the trusses were included in the fire model while all other parts were rounded off.

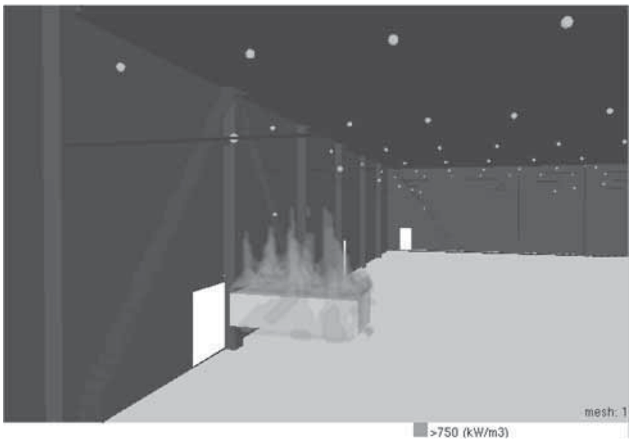


Figure 5.1.29. The ice resurfacing machine fire.

The time-temperature curve of Figure 5.1.30 shows that the fire was decaying rather quickly. The control points are indicated by the letter ‘B’ followed by the consecutive number of the corresponding member.

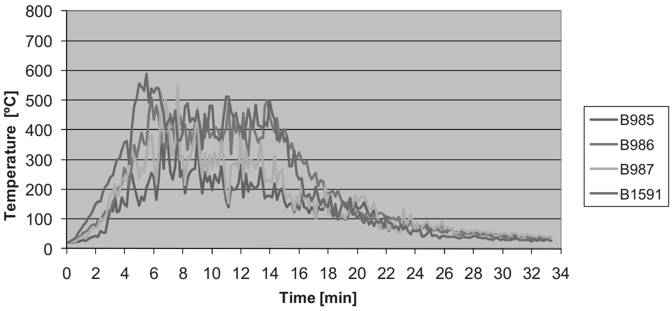


Figure 5.1.30. The highest air temperatures above the ice resurfacing machine fire at various control points.

In the case of the storage fire, burning objects filled the space and flames shot out of the open door. The structures most endangered by the fire were those above the door opening. In Figure 5.1.31 air temperatures are represented by a coloured slice. The other colours of the slice only visualise temperatures while the red objects are structures. The Figure 5.1.31 shows that the ceiling above the door spreads the heat so that the air at the ceiling level is not very hot. On the other hand, the temperatures at the platform just above the door and the column are rather high.

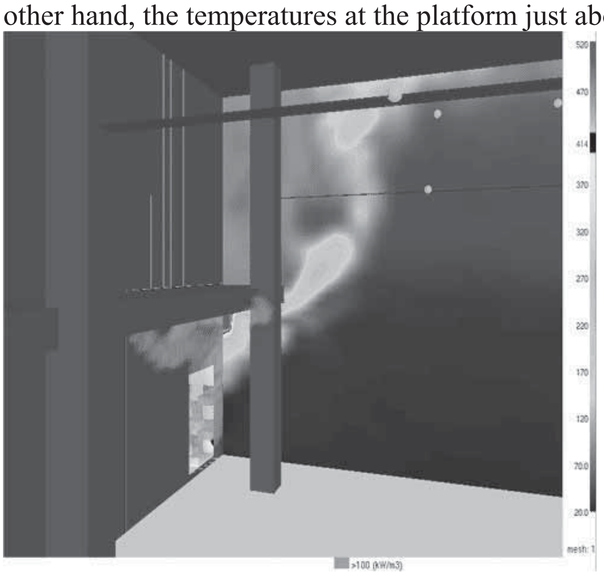


Figure 5.1.31. Storage fire in the ice hall.

The restaurant was modelled in actual size as an open space with all the doors open. Thus, the lack of air did not limit the fire. The burning coat-rack was situated according to architectural drawings. The fine tuning of its position was done by testing when the flames reached the bottom flange of a truss. The fire is visualised in Figure 5.1.32. Air temperatures at control points were not raised above 400 °C.

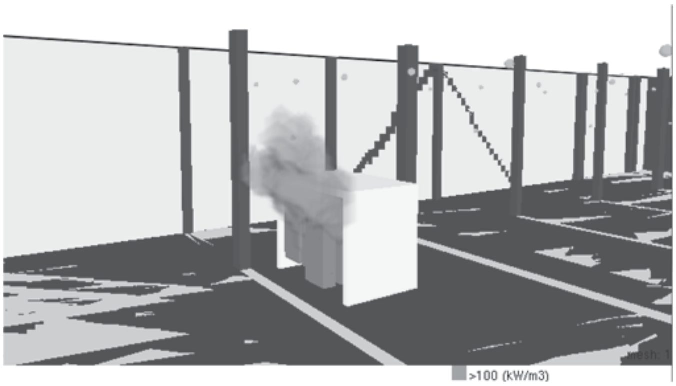


Figure 5.1.32. Coat-rack fire in the restaurant.

The plastic slide fire was situated in an open hall near an open door. No other equipment or possible separating walls were modelled. The fire is visualised in Figure 5.1.33.

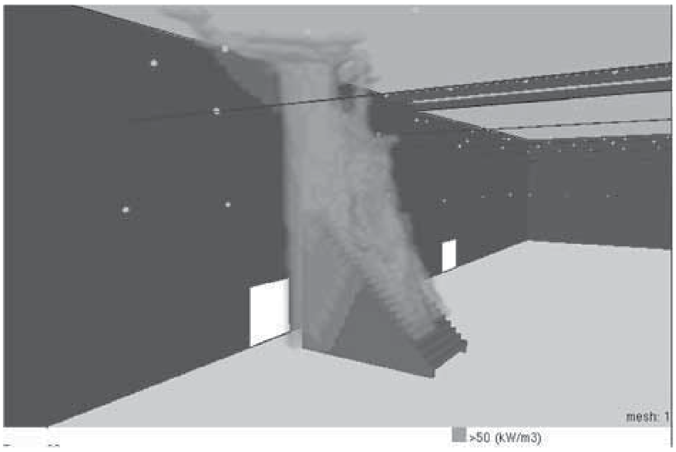


Figure 5.1.33. The plastic slide fire.

The plastic slide fire was very severe although the structure of the slide was thin. Thus, the combustible material was consumed quite quickly as shown by the time-temperature curve in Figure 5.1.34.

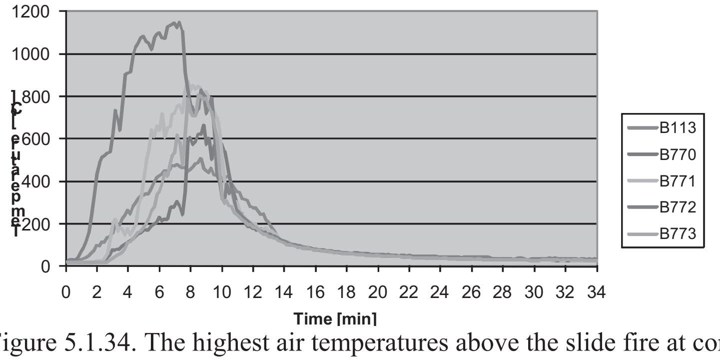


Figure 5.1.34. The highest air temperatures above the slide fire at control points.

In the dance hall model, the entire space was left open. The separating walls were left out of the model in order to produce simulation results on the safe side as the lack of air could not limit the fire. The fire was located near the emergency exit which was modelled open.

Test calculations were made to determine the most severe situation of the stage fire. It was noticed that that tallest speaker caused the highest and longest-standing flames. At the time, the speaker was located under the truss as can be seen from Figure 5.1.35.

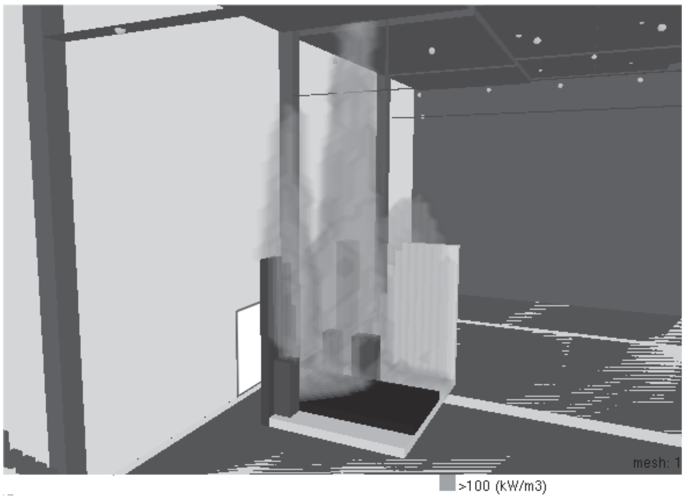


Figure 5.1.35. The stage fire in the dance hall.

The air temperatures caused by the stage fire were not very critical to steel structures as can be seen from Figure 5.1.36.

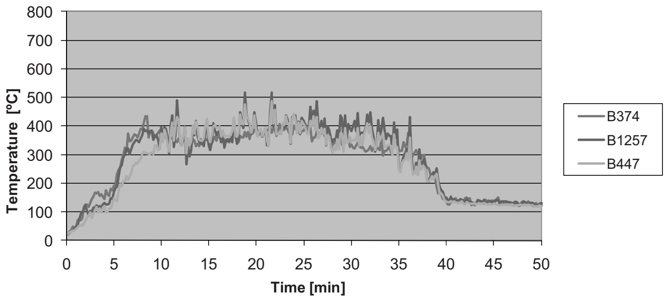


Figure 5.1.36. The highest air temperatures above the stage fire at control points.

Figure 5.1.37 shows the geometrical model of the storey where the volleyball hall is located – without the walls. The calculation grids can be seen as darkened areas on the floor. The thinner grids are indicated by the darkest colour. The perimeters of the grids follow the walls of the hall. The gray doors and ventilation opening are also pictured.

According to Chapter 3.8, only the upper part of the stand is assumed to burn. Therefore, only the seats of the upper part of the stand are modelled.

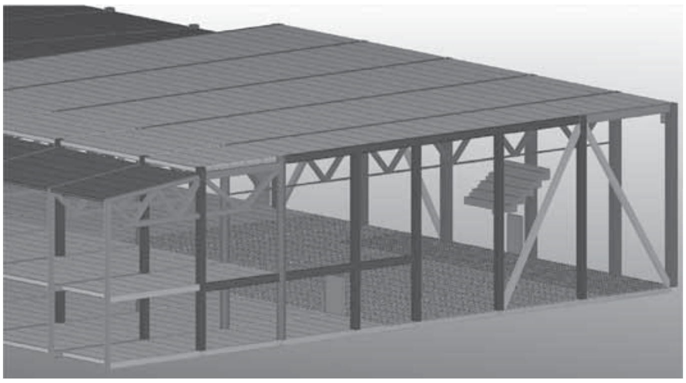


Figure 5.1.37. The geometrical model of the volleyball hall.

The highest point of the flames varied across the stand. The locations of the highest temperatures varied correspondingly. Thus, it was difficult to determine the single most critical spot of the fire. Therefore, the highest registered temperature should be used for all structures above the fire. Figure 5.1.38 also shows how the diagonal braces modelled in green in Figure 5.1.37 have been modified into cubes in the fire model.

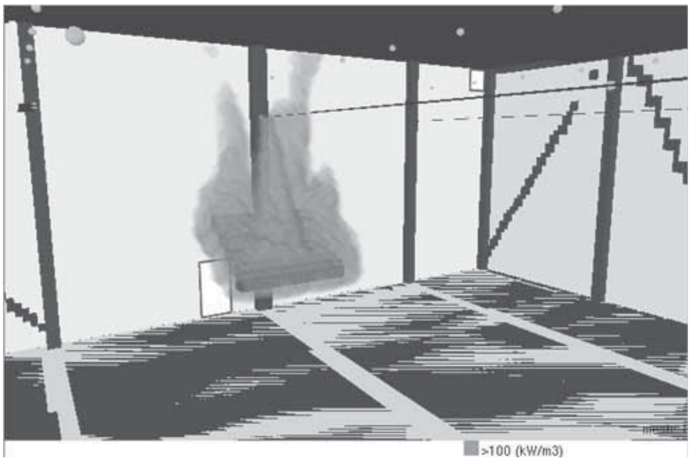


Figure 5.1.38. The stand fire in the volleyball hall.

The air temperatures near the structures were high because the fire spread up towards the ceiling. The duration of the fire was, again, short as can be seen from Figure 5.1.39.

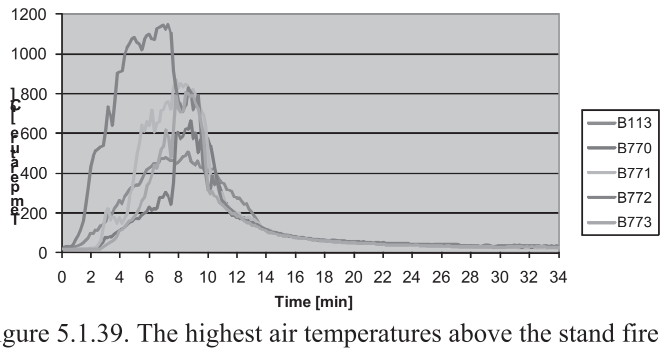


Figure 5.1.39. The highest air temperatures above the stand fire at control points.

The climbing hall was modelled as a three-dimensional multistorey space. Three trusses supported the ceilings. The climbing equipment and plywood based climbing wall were assumed to catch fire. A temperature slice was output also for the climbing wall fire of Figure 5.1.40.

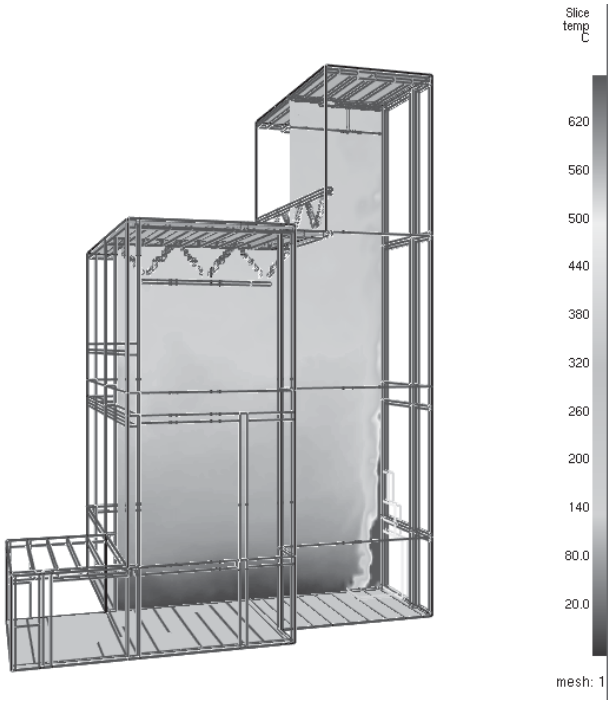


Figure 5.1.40. The climbing hall fire.

Figure 5.1.41 shows that the temperatures of the climbing hall fire were not very critical to the steel structures.

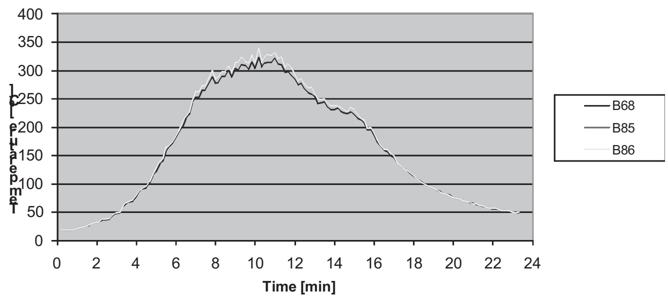


Figure 5.1.41. The highest air temperatures of the climbing hall fire at control points.

All simulation data were delivered to the structural engineer of the project. That allowed him to visualise the simulation results using all temperature histories of all control points. Using this information he could check the resistances of the trusses of every store.

5.1.6 FURTHER DEVELOPMENT

Performance based fire engineering is increasingly used in projects not only for evacuation, smoke control and exit design, but also to determine the resistance of structures in fire. It is not used just to minimise or reduce fire protection, but to enhance the fire safety of structures. In some cases it provides better fire protection than traditional fire design.

Performance based fire design is not suitable only for large projects, but for all projects. It has been frequently applied in a wide variety of projects.

Lot of work will be required in Europe to bring fire design to the same level in different countries, which would make the market for products subject to the same regulations wider. Fire design has been typically incorporated in different sections of national codes as structural codes. In many countries national rules have been changed to allow applying Eurocodes to fire design as required in EU regulations.

The lack of experience and confidence of authorities and design fire definitions seem to be the largest challenges to performance based fire design in projects. The checking of design calculations is a major challenge to authorities.

The article presented a case study on how to define the temperatures of fire compartments. Only the fire scenarios and the definitions of the design fires were given. The structural design of the project was done by others.

Fire scenarios for all the parts of the building were defined in close co-operation with the client, the authorities and other designers of the project. In this kind of performance based design co-operation between all partners to the project is essential and leads to a thorough survey of the worst-case scenarios. The authors believe that the end result is a very high level of fire safety for buildings.

This kind of design requires first rate fire engineering skills and good computing facilities. The developed integrated fire engineering tool was used in the project. In this case a module was used to transfer the data between the product model (Tekla Structures) and the fire simulator (FDS). Careful grid sizing, fitting the obstacles and fire packages to the right locations, etc. require experience from the end user of the system.

Similar integrated systems, in fact the same simulator, FDS, can be used e.g. in evacuation design and other design tasks. High unused potential lies in the integration of design procedures. However, the expertise of skillful engineers cannot be substituted by computers.

Performance based design should be incorporated in design at an early stage of the project. In the case study it was done by the steel contractor at a rather late stage. Earlier introduction could result in improved fire safety over the life cycle and bigger savings during the building phase compared to this project.

ACKNOWLEDGEMENTS

The fire engineering work of this study was done by Dr. Jukka Hietaniemi, VTT, Finland. His input to this project was huge and is gratefully acknowledged.

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