Simulation and Study of Natural Fire in a Wide-Framed Multipurpose Hall with Steel Roof Trusses

D. Pada

In this case study, the structural fire safety of unprotected steel roof trusses in a wide-framed multipurpose hall was evaluated according to the natural fire safety concept. The design fires were simulated with FDS in order to determine the temperature development inside the hall. The temperature of the steel was calculated based on the results from the simulation and the structural analysis was carried out in Robot. It was established that the steel roof trusses could be left unprotected under certain conditions, however, a more violent design fire resulted in failure of the truss.

Keywords: Natural fire safety concept, case study, multipurpose hall, steel roof truss, design fires, sprinkler system, fire resistance, fire simulation, FDS, steel temperature, structural analysis, FEM.

1 Introduction

As a part of an extensive long-term plan for the development of the Helsinki Fair Centre a new 14500 m^2 multipurpose hall will be built in Helsinki, Finland. The design of the hall was carried out in co-operation between Finnish and German architects and it is intended to be able to host both exhibitions and indoor sporting events with up to 6000 spectators. In Fig. 1, the new multipurpose hall can be seen to the left.

The Finnish Building Code allows the fire safety design of a building to be performed according to either the prescriptive regulations or the natural fire safety concept, NFSC. In this study, NFSC was used to do a performance-based structural fire safety design of the steel roof trusses in the above-described multipurpose hall. This made it possible to estimate whether the roof trusses can be safe in the case of fire without passive fire protection, such as intumescent painting.

2 Structure description

2.1 General

The main frame of the hall is made up of reinforced concrete columns and three dimensional steel roof trusses. See Fig. 2 for a view of the frame. The frame spacing is 9.0 m, except in the middle of the hall where it is 13.05 m. The span of the roof trusses is 78 m with a splice in the middle of the

Fig. 1: Air photo of the architects' suggestion for the Helsinki Fair Centre

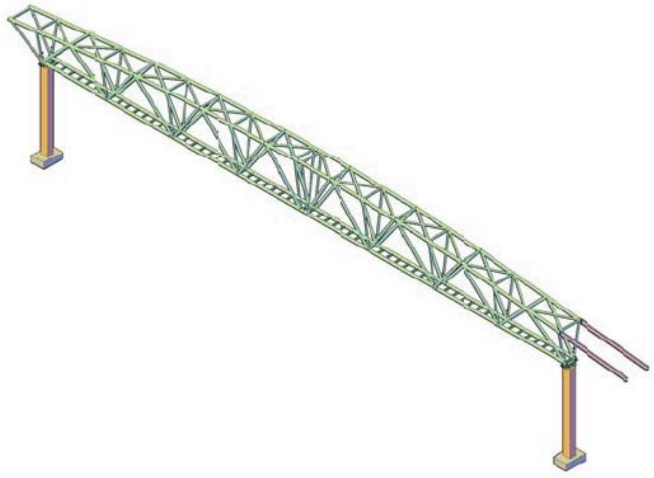

Fig. 2: Main frame

span and the total number of trusses is 17. The free height inside the hall varies from 10 m to 16 m. The total length of the building is just over 170 m and the total width is about 88 m.

The height of the steel roof trusses varies between 4.5 m and 7 m, the bottom width of the truss is about 1.3 m and the top width is 3.0 m. The trusses are made up of structural steel hollow sections of varying dimensions with a steel quality of S355.

The roof structure will consist of wooden elements with mineral wool insulation supported by the roof trusses. A large part of the exterior walls will be made of glass, which is assumed to break when the temperature reaches 200 °C. The rest of the exterior walls will be made of steel sheets with mineral wool insulation and concrete sandwich structures.

The new hall will form one single fire compartment together with an existing hall at the Helsinki Fair Centre. Hence the total area of the fire compartment will be in the order of 33000 m^2.

2.1 Fire resistance requirement

This study focuses only on the first part of the essential requirement for the limitation of fire risks according to the Construction Products Directive 89/106/EEC, i.e. "The load bearing resistance of the construction can be assumed for a specified period of time" [1]. The required time period in this case study was 60 minutes.

3 Design fires

Two prescribed design fires were used in this study. They were chosen from the project's performance-based fire safety design report [2], where a rough risk analysis was made and several different fires were considered, and a report by Hietaniemi [3]. The choice of the design fires from these reports was based on the possible severity of their effect on the steel roof trusses.

3.1 Spectator stand fire

The spectator stand fire represents the case when the multipurpose hall is used for e.g. indoor sport events or concerts. As spectator stands can also be placed above floor level, the design fire is closer to the roof than a fire on floor level, hence posing a larger threat to the load-carrying structure.

According to Hietaniemi [3], the maximum rate of heat release, RHR, of the seat material for a spectator stand fire can be assumed to be 2000 kW/m^2, giving a maximum RHR of the spectator stand of 1500 kW/m^2, while the total fire load is 510 MJ/m^2. The studied spectator stand section measured 8.0 m$\times$13.6 m with a height of 3 m. It was placed 5.2 m above floor level in the lower part of the hall, leaving only about 2 m of free height to the bottom chord of the roof truss. The whole section was assumed to be on fire, giving a maximum RHR of 163.2 MW. Fig. 3 presents the RHR curve for the spectator stand design fire.

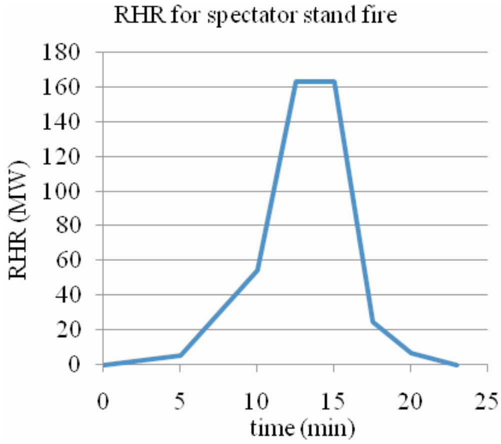

Fig. 3: RHR curve for spectator stand fire

3.2 Exhibition stand fire

The exhibition stand fire represents one of the main purposes of use, where the fire load can be very high. Also this design fire was based on Hietaniemi's report [3], a 10 m$\times$10 m exhibition stand, made of burnable materials, for small motor vehicles, e.g. motorcycles or ATV's, placed on floor level in the lower part of the hall just below a roof truss. The maximum RHR of the design fire was 53 MW, the total fire load was 1720 MJ/m^2 and the height of the stand was assumed to be 2 m. The RHR curve for the exhibition stand fire is shown in Fig. 4.

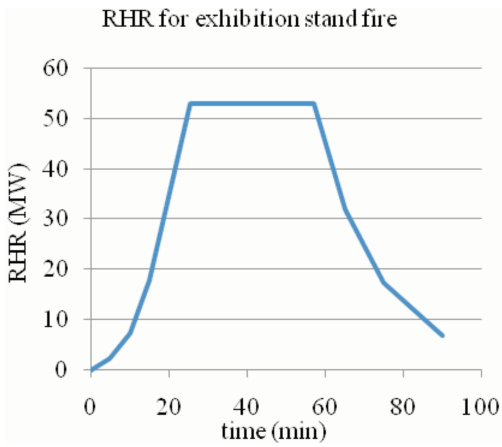

Fig. 4: RHR curve for exhibition stand fire

3.3 Sprinkler system failure

As the sprinkler system is usually considered to be one of the most effective and reliable active fire protection systems in a building, a total sprinkler system failure was not considered in this study. However, a partial sprinkler system failure, where two nozzles above the design fire were inoperative, was considered in both the design fires.

4 FDS model creation

4.1 General

The design fires were simulated with Fire Dynamics Simulator, FDS, version 5.2 and the input files were made with Pyrosim. The whole multipurpose hall was modeled in Pyrosim with a cell size ranging from 0.2 m×0.2 m×0.2 m to 0.8 m×0.8 m×0.8 m, hence the total number of cells was kept at about 2 millions.

4.2 Sprinkler system

The model was equipped with an automatic sprinkler system that activated when the temperature of the nozzle reached 74 °C. The effect of the sprinklers on the gas temperature and the combustion occurring in the gas phase were taken into account in the simulation. The suppressing effect of the sprinklers on the design fire was however not taken into account in the two original simulations, as there was no way of determining how large the effect could be without carrying out real fire tests. In a second additional simulation of the spectator stand fire, the effect was however taken into account according to a method described in Hietaniemi's report [3]. According to this method, the RHR is only allowed to double from the value it has when the sprinkler system is activated. As the model was so large, the time when 20 nozzles had been activated in the original simulation, i.e. at approximately 7 minutes into the simulation, was used as the sprinkler activation point. At that point the RHR was about 28 MW and was hence allowed to grow to 56 MW.

4.3 Smoke exhaust system

The model was also equipped with a smoke exhaust system. The hall was divided into different smoke sections so that one section was about 2400 m2, assuming that that the system could be active only in two sections at the same time. The time at which the smoke exhaust system was activated in the spectator stand fire was assumed to be 400 s and in the exhibition stand fire 600 s. These times were approximated based on simulation tests of the sprinkler activation times, assuming that the smoke exhaust system would be activated roughly at the same time as the sprinklers.

4.4 Data measured

The most important data measured during the fire simulation, from the point of view of structural fire safety design, was the adiabatic surface temperature every 5 m of the bottom chord of the steel roof trusses situated above and near to the fire. The adiabatic surface temperature is the temperature that the bottom chord "sees", and is the quantity that is representative of the heat flux to the solid surface [4]. This temperature was used to calculate the temperature of the steel cross section.

The gas temperature of the building was also measured at several different heights and points to get a picture of the total temperature development in the building as a function of time.

5 Simulation of fire

5.1 Spectator stand fire 1

The original spectator stand fire simulation was ended at 1400 s, as the fire only lasted 1380 s. The RHR reached a maximum value of 167 MW during the simulation, i.e. very close to the intended value of 163.2 MW. The first sprinkler nozzle activated a bit sooner than expected, already at 308 s, being one of the sprinklers above the fire. In total 251 out of the 310 functional sprinkler nozzles in the model were activated during the simulation.

The temperature inside the hall remained quite low in general, except of course over and near to the fire. Close to the roof the temperature reached about 65 °C, while at 5 m above floor level it remained just above 20 °C.

The measured adiabatic surface temperature of the bottom chord just above the fire is plotted in Fig. 5, and this was also the measurement used to calculate the temperature of the steel.

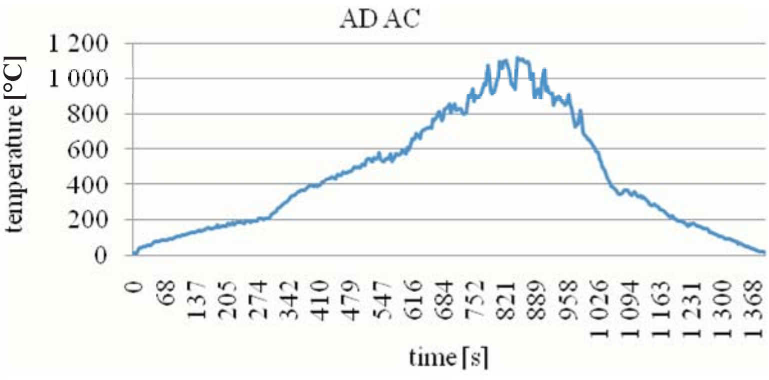

Fig. 5: Adiabatic surface temperature of the bottom chord above spectator stand fire 1

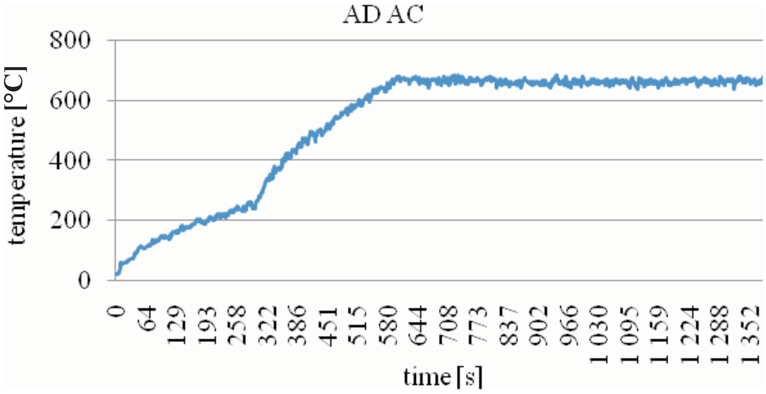

Fig. 6: Adiabatic surface temperature of the bottom chord above spectator stand fire 2

5.2 Spectator stand fire 2

In the additional simulation of the spectator stand fire, where the suppressing effect of the sprinklers on the design fire was taken into account, the RHR reached a maximum value of 56 MW.

As the sprinklers were removed from the model in order to speed up the simulation, the only measured data taken into consideration was the adiabatic surface temperature of the bottom chord just above the fire. This temperature is plotted in Fig. 6.

5.3 Exhibition stand fire

The exhibition stand fire was ended at 3670 s, as there was no need to study the fire situation beyond one hour. The maximum RHR measured during the simulation was just over 53 MW, i.e. almost exactly the intended value. The first sprinkler nozzle activated a bit later than expected, at 668 s. In total only 148 out of the 310 functional sprinkler nozzles were activated.

The temperature close to the roof reached circa 60 °C, while at 5 m above floor level it increased only a few degrees above the original temperature of 20 °C, again except close to and over the fire.

The adiabatic surface temperature of the bottom chord above the fire is plotted in Fig. 7.

6 Fire safety design of the steel roof truss

The temperature development of the unprotected steel members was calculated according to Eurocode 1 and 3 just above the fire. The temperature was assumed to be vertically equivalent.

6.1 Steel temperature

In the original spectator stand fire the maximum temperature of the bottom chord with a wall thickness of 10 mm was established to be 727 °C, whereas it was 897 °C for the diagonals with a wall thickness of 5 mm.

In the additional simulation of the spectator stand fire the temperature of the bottom chord reached 614 °C, whereas the diagonals reached a temperature of 661 °C.

In the case of the exhibition stand fire, the maximum temperature of the bottom chord was 387 °C and the maximum temperature of the diagonals was 396 °C, i.e. almost the same temperature was reached in all steel sections, independent of wall thickness.

6.2 Structural analysis

An FEM-model of the roof truss was made in Robot Millennium 21. In the model the truss was subjected to snow load, self-weight of the roof structure, self-weight of equip-

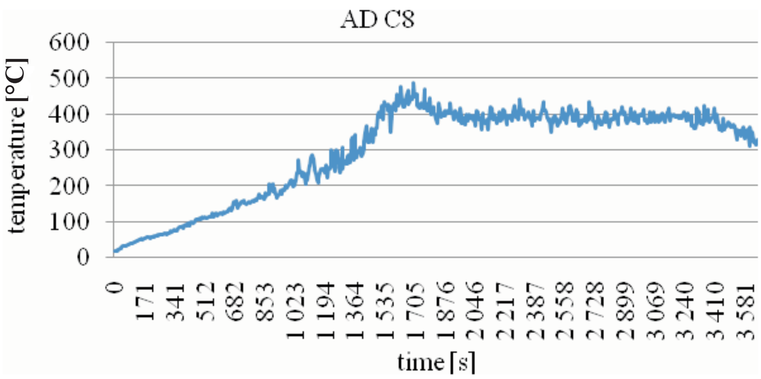

Fig. 7: Adiabatic surface temperature of the bottom chord above the exhibition stand fire

ment such as lighting and ventilation ducts hung to the bottom chord of the truss, and of course the self-weight of the truss itself. The temperature of the truss was assumed to be uniform in order to simplify the calculations and to avoid having to take the effect of heat conduction inside the roof truss into consideration. The effective yield strength and the modulus of elasticity of the steel were changed to correspond to the values at the different elevated temperatures.

With the help of the FEM-model the critical temperature of the roof truss could be established to be 590 °C. At this temperature the highest degree of utilization was 0.94 and took place in the diagonals in compression closest to the ends of the truss. The deflection was established to be 400 mm in the middle of the truss, without taking the pre-camber of 100 mm into consideration. Hence the actual deflection would be in the order of 300 mm, which equals the length of the truss, 78 m, divided by 260.

7 Conclusions

By comparing the temperature of the steel reached in the different design fires with the critical temperature of the truss, it could be established that the truss could well withstand the exhibition stand fire without any fire protection. However, in the case of the spectator stand fire the temperature proved to be too high for the unprotected truss to endure the fire, though the temperature did not rise very much above the critical temperature when taking into account the suppressing effect of the sprinklers on the fire.

References

[1] European Committee for Standardization. SFS-EN 1991-1-2 Eurocode 1: *Actions on structures. Part 1-2: General Actions. Actions on structures exposed to fire*. Finland: Finnish Standards Association, 2003.

[2] Hämäläinen, S.: *Toiminnallisen palosuunnittelun määrittely ja käytettävät lähtöarvot, Suomen messut*. Helsinki, Finland: Näyttelyhallin laajennus, 12. 06. 2008.

[3] Hietaniemi, J.: *Palon voimakkuuden kuvaaminen toiminnallisessa paloteknisessä suunnittelussa*. Finland: VTT, 2007.

[4] McGrattan K. et al.: *NIST Special Publication 1019-5, Fire Dynamics Simulator (Version 5) User's Guide*. Washington, USA: U.S. Government Printing Office, 2007.

Dan Pada
e-mail: Dan.Pada@ako.fi

Helsinki University of Technology
Faculty of Engineering and Architecture
Espoo, Finland

