FIRST STEPS ON PARAMETRIC STUDY WITH FDS FOR LOAD-BEARING STRUCTURES WITHIN HOLLOW SPACES

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INTRODUCTION

In Germany, there are currently no standard regulations suitable for designing load-bearing structures within hollow spaces in a cost-efficient method. The current codes for fire design have many restrictions such as limiting the fire sections to be below 400 m², heights of hollow spaces to be either less than 20 cm or 50 cm depending on their usage or the maximum allowed fire loads to be lower than 7 kWh/m² [6] [7] [8]. Once any of these limitations is exceeded, certain fire resistance ratings are applied, which means that the inner load-bearing steel structures must be designed using standard temperature-time curve [9] or passive fire protection measures are needed. Therefore this national research project is funded by AiF e.V., German Federation of Industrial Research Associations (project no. 18894N) and FOSTA e.V., Research Association for Steel Application (project no. P1139) to determine a natural fire scenario for the design of hollow spaces and investigate the effect of this natural fire on composite dowels in composite slab structures.

CURRENT SITUATION AND OBJECTIVE

Integrated steel construction poses an economical and sustainable way of construction, but due to the strict regulations of Model Building Code [5], the steel structure needs to be designed for fire situation or cladded with fire protection materials, once certain limitations are exceeded. Employing a natural fire scenario, instead of standard temperature-time curve according to ISO 834 and DIN EN 1991-1-2 [9] in the design of hollow spaces is not only beneficial for the design of integrated steel construction, but it may also simplify the design of current system of suspended ceilings as well as raised and hollow floors.

This paper deals with the issue of geometrical boundary conditions and fire loads in fire situation in hollow spaces. To achieve this objective, computational fluid dynamic (CFD) is used to perform a parametric study on important factors. Refer to subchapter “Boundary conditions for parametric study” for the listing.

In later phase of the project, which is not part of this paper, the chosen boundary conditions will be validated using real fire tests. When the bench-size (small scale) simulations are validated, CFD will then be used to predict and derive simplified fire models for fire scenarios in hollow spaces using complete models. To round up all possible scenarios, real-size fire tests are further planned for the scenario of “fire from top of the hollow space” and “fire from bottom of the hollow space”, which will use the standard temperature-time curve [9] as the fire load.

As mentioned before, the determination of the load-bearing capacity of composite dowels using the natural fire scenario in hollow spaces will also be part of this research and will be conducted by the research partners, Mr. Patrick Meyer, M. Sc. and Prof. Dr. -Ing. Peter Schaumann from Leibniz University Hannover (LUH)

COMPUTATIONAL FLUID DYNAMIC (CFD) FOR PARAMETRIC STUDY

Introduction to program

Fire Dynamics Simulator (FDS), developed by The National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce, is chosen for the parametric study. "FDS is a computational fluid dynamics (CFD) model of fire-driven fluid flow, which solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires" [11].

To simplify the graphical input of FDS, PyroSim from Thunderhead Engineering Consultants, Inc. is used as a preprocessor [12] and the post processor used is Smokeview [11]. Following versions of these programs are used for the parametric study:

- FDS: Version 6.3.2
- PyroSim: Revision 2016.1.0425
- Smokeview: Version 6.3.2

Model / Geometry

To limit the scope of the research project, the natural fire scenario is considered only for hollow spaces in office and administration buildings. As the typical fire section area is normally 400 m², the real-scale simulation should also have the same ground area.

However the simulation time for a 400 m² ground area with certain fineness of meshes is too long for it to be feasible for the parametric study. Hence it was decided to perform the parametric study on a smaller geometry. As most installations in hollow spaces concentrate on a small area in the corridor, the chosen geometry represents the area located directly in front of the vertical installation shaft or sub-distributor. The width of the bench-scale simulation, named "1st Model" is chosen to be 2.0 m, because the width of most corridors are between 2.0 m to 2.5 m, It was also decided, that the bench-scale model will have a length of 3.0 m and a height of 0.2 m, 0.4 m and 0.6 m. Refer to subsection "Clear Height" for the explanation of the chosen heights.

The biggest advantage of the 1st model is the faster simulation time, which allows many parameters to be tested. However like all bench-scale simulations, the transferability of the results compared to real-scale results is not easy. The biggest challenges are how to supply enough ventilation in the smaller model to replicate the scenario of a fire in a 400 m² "room" and how the fire loads should be scaled to provide similar results as the real-scale simulation. Therefore it was decided to simulate a 400 m² hollow space, so that the results from the real-scale simulation can be compared to the bench-scale results and used as part of validation process. Therefore a 2nd model is created with a dimension of 20 m x 20 m as well as a clear height of 0.2 m, 0.4 m and 0.6 m. The validation of small and large simulations is not part of this paper.

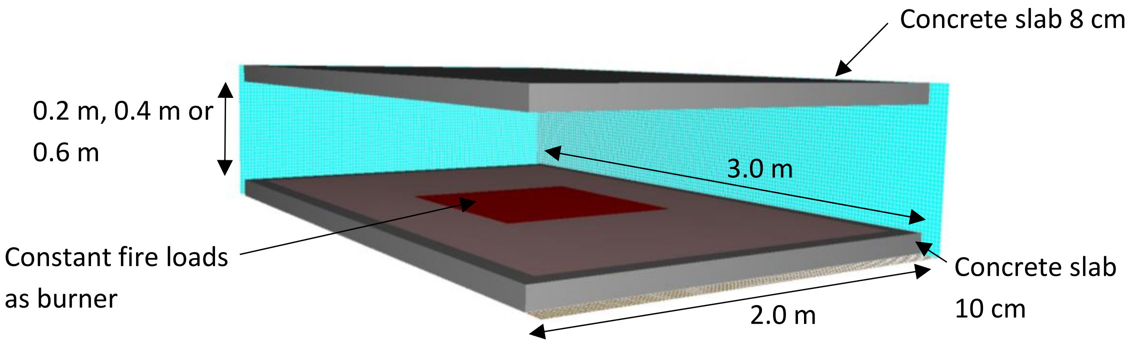

*Image 1 Geometry of 1st model in bench-scale simulation (*the outer walls of 8 cm calcium silicate panels with ventilation openings are hidden for illustration purposes)*

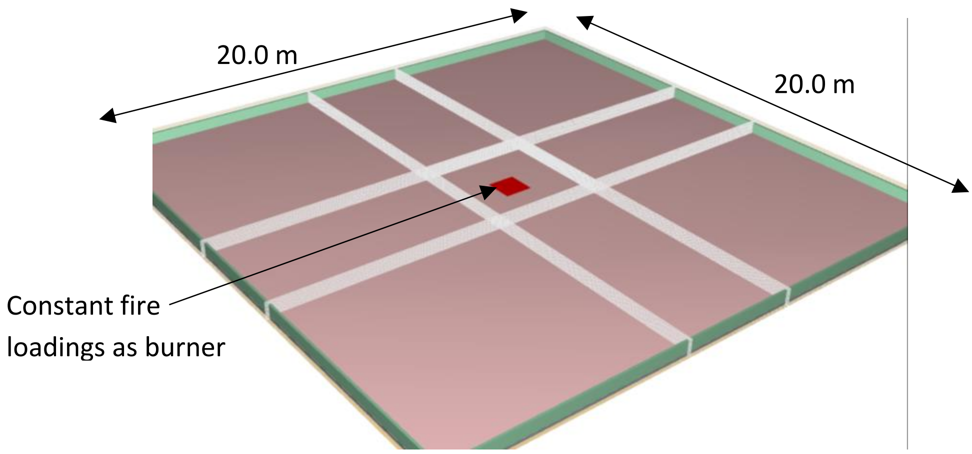

*Image 2 Geometry of 2nd model in planned real-scale simulation (*the top slab of 8 cm concrete slabs with/without ventilation openings are hidden for illustration purposes)*

Another major focus in this paper is also to determine the fire scenario in an integrated slab system in composite structures, similar to the construction in research project P879 [2]. Thus a 3rd model will be simulated in later phase to study the effect of a fire in hollow spaces on the load-bearing structure, refer to image 3.

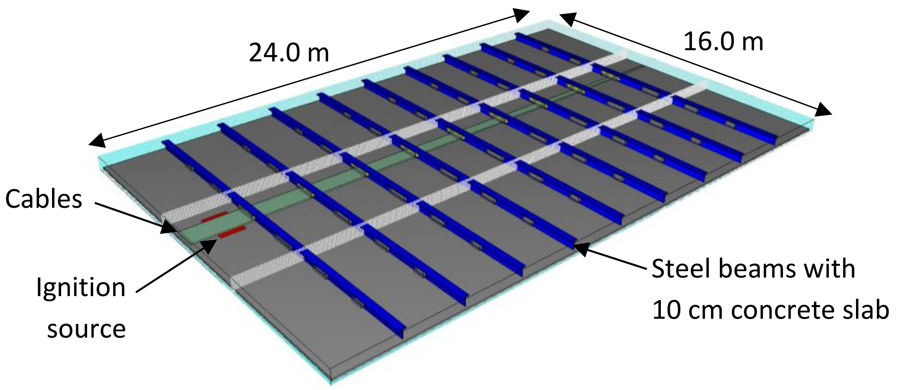

*Image 3 Initial geometry of 3rd model with clear height of 39.5 cm in future simulation (*the top slabs and side walls are hidden for illustration purposes) (Simulation is modelled after [2])*

Fire loads

Apart from the geometry, the next most important parameter is naturally the fire load. For this purpose, an online questionnaire and some interviews with electric engineers and building service planner were conducted.

Common installations with their flammability as found in hollow spaces in Germany are summarized as following:

- Electric cables: flammable to hardly inflammable
- Heating and cooling ducts: about 2/3 of the used material are non-inflammable and the rest is hardly inflammable
- Inspection ports or floor outlets: flammable to non-inflammable
- Sanitary pipes: about half of the used materials are non-inflammable, another 40% hardly inflammable and about 10% burnable
- Sprinkler piping: all used materials are non-inflammable
- Ventilation ducts: all used materials are non-inflammable

To limit the scope of the research project, the ignition source will not be defined. It will be assumed, that electric cables ignite themselves, even if the chances for a short circuit, which will lead to fire, are low. Another possibility may be a fire starting from floor outlet due to short circuit of external components, such as vacuum cleaner or PC, which are connected to the floor outlets.

For our research project, the main fire load is decided to be the electric cables and the secondary fire loads are the floor outlets as well as insulation. For the parametric study, the simplified fire loads in a fire section of 400 m² are determined using typical electric cables used in an office and administration buildings:

- Maximum no. of working station possible with a minimum area of 8 m² [1]: 50
- Assumption: No. of heavy current cables 5x1.5 mm or 3x2.5 mm (0.58 kWh/m) per working station = 2 and no. of data cables Cat. 7 (0.161 kWh/m) per working station = 4 [10]
- Governing fire load density located directly in front of vertical shaft or sub-distributor with chosen 50% additional factor (Area = 1 m²) = 92 kWh/m²

The total fire loads for heavy current and data cables according to the interviewers is about 2180 kWh within a standard 400 m² in office and administration buildings. As comparison, the total fire loads according to research project “Inadeck” [2] is about 1514 kWh and the fire density is about 105 kWh/m². The simplified fire load density for this paper is based on 300 cables within 1 m² and research project “Inadeck” [2] used 188 cables. Comparing both boundary conditions, research project “Inadeck” [2] assumed 40 working stations and our calculation is to be on the safe side with 50 working stations.

The above comparison shows that further research in later phase in this research project is required before the governing fire load for the design of fire scenario in hollow spaces can be determined. Therefore for the parametric study in the initial phase, the simplified fire load density of 92 kWh/m² is applied.

FDS/PyroSim allows few methods for inputs of fire loads, which includes constant heat release rate (HRR) per area, HRR over time and mass loss rate using heat of combustion over time. The former input is chosen for the parametric study, because using two variables at the same time will complicate the comparison of the effects. As the input requires the heat release rate per unit area (HRRPUA) in kW/m², the duration of the simulation needs to be considered to analyze realistically the effects of the simplified fire loads.

For this purpose, pre-simulations are conducted to find suitable fire load for the simulation. Theoretically for a simulation of real time of 20 seconds, the HRRPUA should be 16560 kW/m² (3600/20 = 180 times of 92 kWh/m²), assuming that the cable can burn 60 minutes. However as seen in image 4, the fire in lower hollow spaces is ventilation controlled and a too high fire load is unfavorable, as the produced smokes hamper the fire and extinguish it.

It is decided to choose 920 kWh/m², 10 times of 92 kWh/m², as the main fire load, which represents the fire loads before the temperature curve in image 4 becomes horizontal. It is also beneficial for the study of effect of different boundary conditions except the raise of temperature in a material, as it lowers the simulation time tremendously while maintaining the basic principle of equivalent fire duration. To analyze the raise of steel's and concrete's temperature, the realistic HRR must be applied due to the heat conduction of the materials, which will be conducted in future phases.

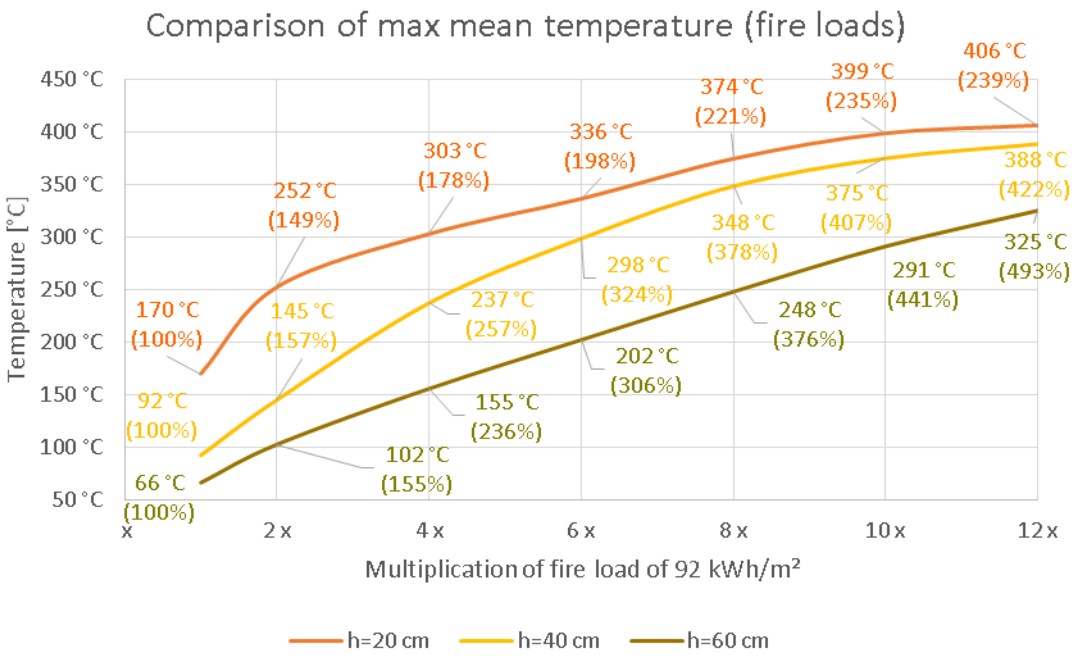

Image 4 Comparison of max mean temperature, depending on the fire loads for hollow spaces with a clear height of 20 cm, 40 cm and 60 cm.

Boundary conditions for parametric study

All possible boundary conditions, which can affect the results of fire in hollow spaces are listed below.

- Fire load density
- Meshes and cores vs. simulation time
- Clear height
- Ventilation
- Ambient temperature*
- Position of main fire load (electric cables)*
- Chimney effect*
- Steel and concrete properties*
- Dimensions (Small structure vs. large structure)*

The boundary conditions marked with * are not part of this paper, as this required the correct input of the fire load with the appropriate real time or simulation on real-scale models. All other boundary conditions, apart from the position of main fire load (electric cables) can be conducted initially in the bench-scale 1st model.

Meshes and cores vs. simulation time

After deciding on the geometry and fire loads for the simulation, the next important step is to choose suitable meshes and cores. Meshes are important for CFD simulations, as all calculations are based on meshes and choosing it is usually based on one of the three criteria.

The first criteria, which is also one of the biggest disadvantage of FDS, is that all objects must conform to the meshes. When object's geometry does not conform to the meshes, the object's geometry will be distorted to match the chosen meshes. As shown in image 5, the beam in a simple fire simulation in an open car park has changing geometry over the length in the area outside of the burning cars due to coarser meshes [3].

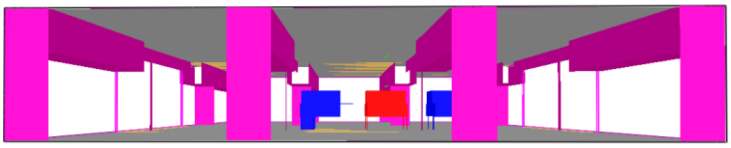

Image 5 Coarse vs. fine meshes in a simple fire simulation [3]

Further criteria is a suggestion from FDS User's Guide [4], which is to determine the mesh size using the characteristic fire diameter (D*), which depends on $\dot{Q}$, the heat release rate in [kW], ρ_∞, the density in [kg/m³], c_p, the specific heat in [kJ/kgK], T_∞, ambient temperature in [K] and g, gravity, which is 9.81 m/s². The recommended mesh size is then between D*/4 to D*16.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \quad (1)$$

Another important criteria is the simulation time. It is always possible to have a very fine mesh to accomadate the needed geometry and the recommendation from FDS, but a finer mesh does not necessary means better results, while lengthening simulation times unnecessarily. As seen in image 6 and 8, the mean gas temperature decreases both in the 1st and 2nd model, as finer meshes are used. This phenomenon is observed in the simulations and may be compared to the problem of singularity in Finite Element Method (FEM).

Using the 1st model, simulations using the same boundary conditions with different meshes were conducted. The result with 10 cm coarse mesh deviates at the average temperature too much from the other simulations. Refining the mesh beyond 2 cm will push the simulation time exponentially high, which will make a parametric study near to impossible within the given time frame.

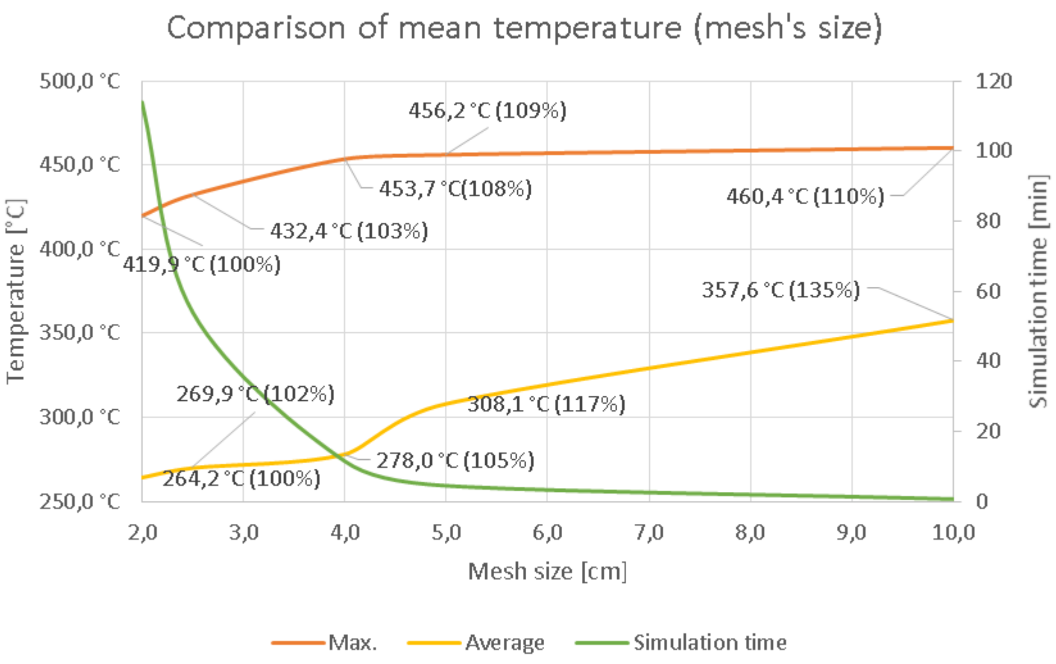

Image 6 Comparison of max and average mean temperature as well as simulation time, depending on the mesh size

Balancing all three requirements, it is decided to have a 2 cm mesh for the bench-scale model, which allows a realistic geometry and yet maintaining feasible simulation time. The realistic geometry is important, as with increasing mesh size, the dimension of members such as walls, slabs and cables are distorted and the simulated model represents no longer the reality, compare image 5.

For the 2nd and 3rd model, the first thing to consider is the possibility of parallel processing, which can shorten the simulation time tremendously, when chosen correctly. When the meshes are divided, FDS supports parallel simulation by assigning them to different cores or computers (clustering).

However a few rules need to be abided, which include not dividing the ignition source and choosing a suitable sequence, as it is not advantageous, when meshes need to wait for the results from other meshes.

For this purpose, simulations with different divisions are tried on a 16-core processor. Considering a fire in the middle, 9 and 13 divisions, refer to image 7 are simulated and the results are compared, refer to image 8.

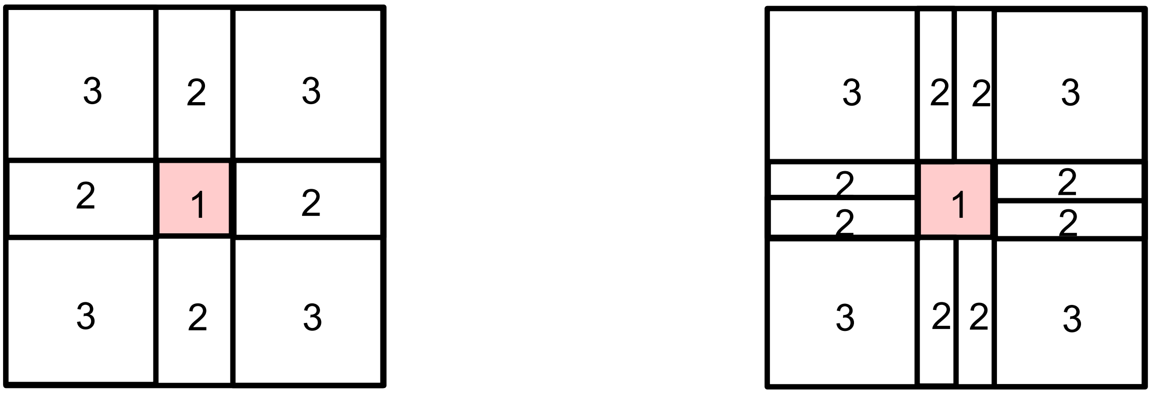

Image 7 *9 and 13 mesh divisions for 2nd model with a base area of 20 m x 20 m. The number depicts the sequence of calculation.*

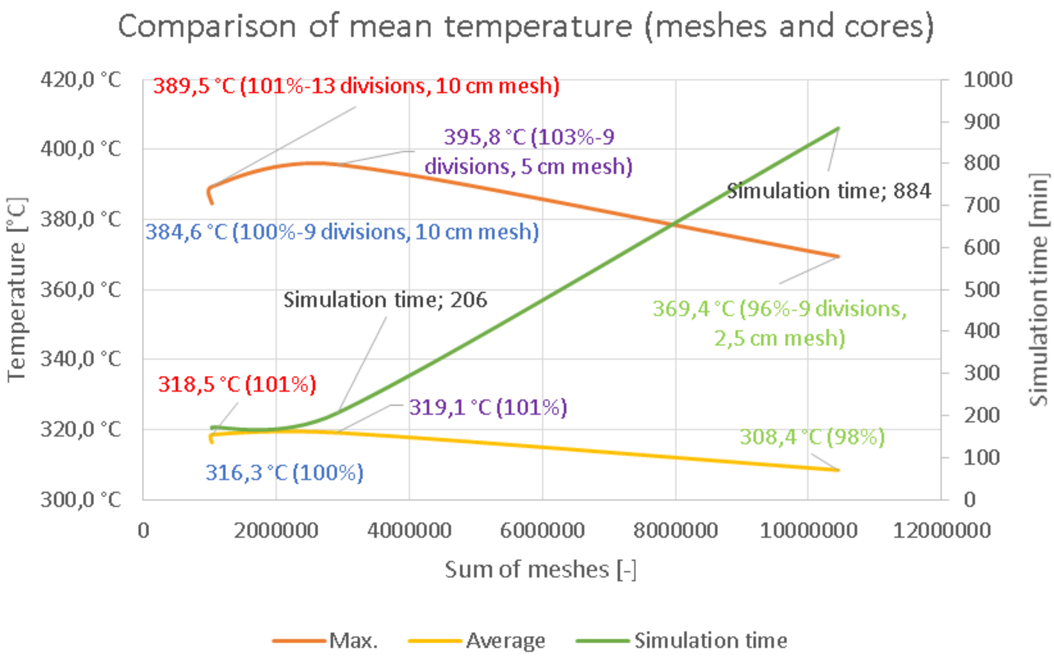

Image 8 *Comparison of max and average mean temperature as well as simulation time, depending on number of cores and outer mesh size. The fire mesh size remains at all time at 2.5 cm.*

The temperature distribution between 9 and 13 divisions as well as simulation time are very similar, refer to image 8. However, once the temperature distribution in the model, refer to image 9, is compared, the result from 13 divisions is not understandable and thus it will not be used for further simulations. On a side note, when a simulation with 9 divisions can deliver the same result as a 13 divisions, then 9 divisions should be used, as it opens up other resources within the same computer.

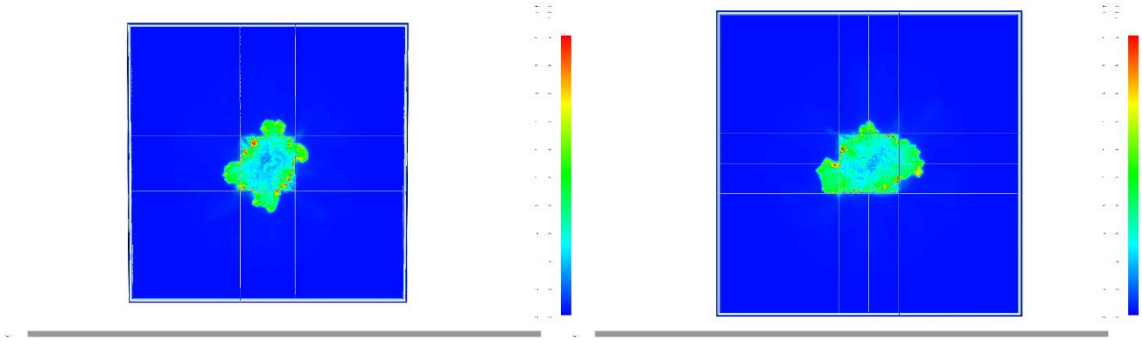

Image 9 Temperature distribution for 9 and 13 mesh divisions for 2nd model with a base area of 20 m x 20 m. [Left: 9 divisions and right: 13 divisions]

For further simulations with 2nd model, 9 divisions with a mesh size of 2.5 cm within the fire mesh and 5.0 cm in outer area is used, because the distribution of the fire and the simulation time are most justified.

Clear height

Until this point, all simulations were conducted using a clear height of 20 cm, which is the typical height of raised or hollow floor systems in normal area, excluding technical rooms. This paper deals with 2 types of hollow spaces, a general hollow space in raised and hollow floors as well as suspended ceilings and hollow spaces within an integrated slab system.

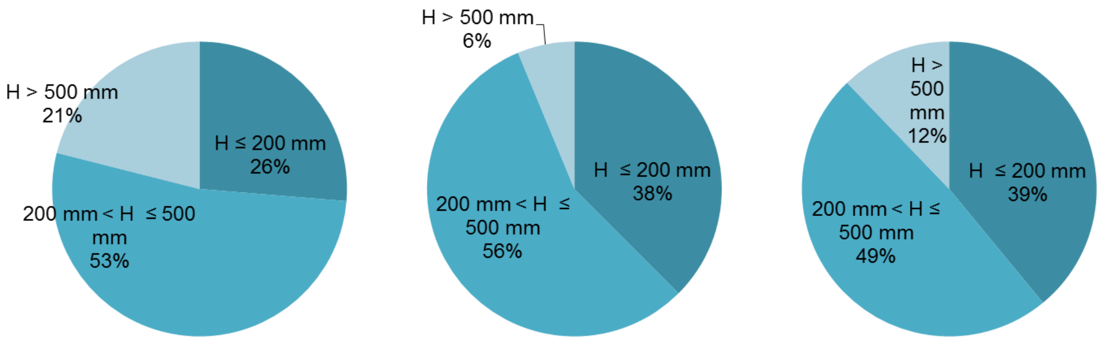

Image 10 Clear heights of hollow spaces according to the questionnaire from TUM (Left: Suspended ceilings, middle: raised and hollow floors, right: all hollow spaces)

Based on the online questionnaire, most of the hollow spaces have a clear height less than 50 cm and in about 10% the case, a clear height of 50 cm and more is recorded. Therefore for further simulations in 1st and 2nd model, a clear height of 20 cm, 40 cm and 60 cm are chosen. As shown in image 4, fire in hollow spaces with a clear height below 60 cm is clearly ventilation controlled and thus it is important to perform the parametric study using three different heights. 40 cm is also chosen, as it is the height of the chosen integrated slab system [2], refer to next paragraph.

The clear height within an integrated slab systems depends on the loads, effective width and span length, as the height of the load-bearing steel structure form the height of the hollow space. Typical heights of some systems, as depicts in [2] are listed below. A clear height of 39.5 cm is chosen for 3rd model, because the system from Inadeck is chosen to be the basic for this research project.

- Inadeck from FOSTA P879: 39.5 cm
- Slimline Buildings: 33.0 cm – 73.0 cm
- Integrierte Massivdecken from TU Wien and RWTH Aachsen: 40.0 cm
- Con4®-XXL Decke: 30.0 cm
- Topfloor-INTEGRAL from Wetter AG: 26.0 cm – 50.0 cm

CONCLUSION

Even though there are no concrete results yet for a fire scenario in hollow spaces at this time, much has been learned through simulations alone. With the help from CFD, parametric studies can be done cost efficiently in a small time frame.

However like any simulation program, the results are only as correct as the input. Therefore huge amount of time need to be invested to learn, try and validate the results, before the results are applicable to the definition of design fires.

Future planned steps of the research project include the comparison of the results from simulation with real fire test, bench-scale simulations with steel profiles and other burnable materials in hollow spaces, as well as simulations with leakage for ventilation, etc.

Conclusively, the results from the parametric study are very promising, as fire in low clear height is clearly ventilation controlled and prove also difficult to spread.

LITERATURE

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