PLANNING ENVIRONMENTS OF STRUCTURES IN FIRE

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ABSTRACT

The design of structures in fire has usually been based on ISO standard fires. For higher quality design the real situation should be analysed more carefully. This would improve the safety level of the structures and in many cases help avoid redundant fire protections.

The method discussed in this paper is the natural fire design documented by [DIFISEK, 2005] where the gas temperatures are based on simulations of realistic natural fires. Fire simulations in this study are done using the FDS program by NIST. The method follows the European standard [EN, 2005] but the design process is still complex. The same building parts should perform smoothly in four different tasks: product modeling, fire simulation, heat transfer from gas to structures, and structural analysis. The utilization of building information models as initial data of fire simulation has been described e.g. in [Dimyadi et al., 2007] and in [Heinisuo et al., 2009]. This paper discusses how different kinds of structural analysis programs can be integrated to the design process and what requirements those programs set for data transfer.

The final goal of the research is practical structural design for entire buildings in fire. In this phase, especially fire simulations need computation time but, for example, accurate and continuum finite element models will not be used for the entire building because of the laborious generation and analysis of the model. The most suitable solutions found so far include structural analysis programs where the members can be modeled as one-dimensional elements, beam elements. The heat transfer from gas to members is solved in the analysis program by applying Eurocode rules. At present, no standard data transfer form used in building projects includes all the entity data needed in these tasks. Very different data are needed in the analysis than, for example, in using continuum models for members.

Keywords: BIM, natural fire design, steel structures.

1 INTRODUCTION

Building information models (BIMs) are widely used especially for steel structures in building projects. They have been found to enhance the design process and the entire building process [Eastman, 1999]. This is accomplished by smooth data transfer between disciplines. Standard data transfer protocols, such as CIMSTEEL [Crawley, Watson, 2003] and IFC, have been developed and used for over ten years. The utilization of BIMs for rather heavy tasks in design, such as fire engineering, has only been considered in a few papers [Outinen et al., 2009] and [Cimyadi et al., 2007]. It is believed that the same benefits are also available for fire engineering as other tasks of building projects.

Considering the natural fire (or performance based fire) design defined in [DIFISEK, 2005], the benefits of BIMs can be clearly seen. Using this concept, only the building under consideration and fires and sprinklers needed for that specific building are studied. In this context the BIMs are perfect data sources for the fire design. We can model the building as is with all required entities, such as walls, floors, members, openings, and transfer the entity data to the fire simulation program. This study uses perhaps the most common program, Fire Dynamics Simulator (FDS by NIST [McGrattan et al., 2007]), for fire simulations. The fire sources and sprinklers with all their entity data needed for the fire simulation are also modeled in the BIM. This study uses Tekla Structures for BIM. No standard data transfer form used in building projects currently includes all the entity data needed in data transfer between the BIM and the FDS. This problem has been studied in [Heinisuo, Laasonen, 2007] with respect to geometrical entities in general, and in [Heinisuo et al., 2008b] as to particular obstacles. The most important entity to be transmitted from BIM to FDS is the computational grid of the FDS program. , Correct grid sizes should be used to ensure the accuracy of the results from FDS. The rules to define correct grid sizes are given in [Heinisuo et al., 2008a]. Different spaces typically require different sizes of grids.

The results of fire simulations can be used in fire engineering for such tasks as determining smoke and toxin propagation, and evacuation planning. In this paper is discussed on the analysis of resistance of steel structures in natural fires. Checking the resistance of steel structures requires first an analysis model for the steel structures. Most BIMs include protocols for data transfers from BIM to the structural analysis model. The structural analysis model can be an entire three-dimensional continuum based on the finite element method (FEM). However, in existing practical applications using the most advanced computing systems, this method can only be used for limited problems, mainly for considering some details of steel structures, not the entire frames. In this study the analysis model involves the composition of one-dimensional finite elements, beam elements. This way not only the members, but also the joints of steel structures, can be analysed in fire both in 2D [Leston-Jones, 1997] and in 3D [Heinisuo et al., 2009].

Data transfers from BIMs to structural analysis programs have been completed using 1) standard data forms, 2) input files of structural analysis programs, or 3) special in-built or 4) home-built programmed macros which work well when constructing the structural analysis model for ambient conditions. In fire analysis different data are needed for structural members than for ambient conditions. These data include Young's modulus, thermal elongation, conductivity, emissivity, shading factor, many of which are dependant on the temperature of steel. These data are needed in data transfer between BIM and FDS, too, if steel members are modeled in the FDS. The data transfer protocols used in BIMs does not include these data.

The temperatures of steel structures are needed to analyse steel structures in fire. In this study the gas temperatures near the steel members and joints are transferred from the FDS based on [Outinen et al., 2009]. These data are used to calculate the steel temperatures. The solving of the heat transfer from the gas near the steel members and joints to the steel material is the focus of this paper. Problems and some proposals for their solution are given. The estimation of joint temperatures of steel structures is proposed.

2 ALTERNATIVES FOR REALIZING THE DATA PROCESS

2.1 The natural fire design process

The natural fire simulation process defined above can be described by the three boxes shown in Fig. 1. The analysis program box plays the key role when considering the main result of the process: "Are the resistances of structures in fire sufficient?" Its features determine how accurate the result will be. Limitations can be set for other phases of the process but they cannot remedy any possible weaknesses of the analysis program. The requirement for the data transfer is that even if the input data of the analysis come from several sources, they have to suit the same model.

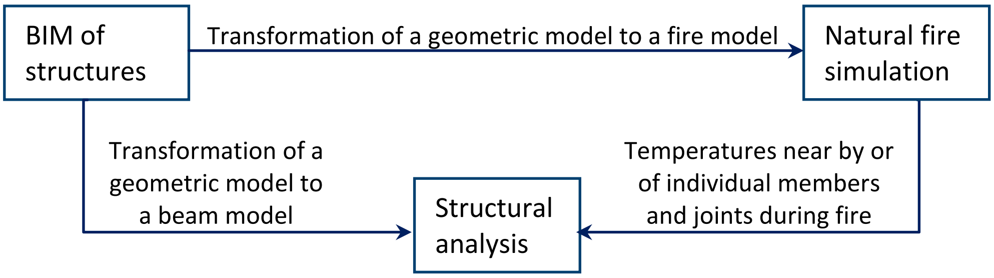

Figure 1: The input data of structural analysis in the fire design process.

Many practical issues have to be decided before the calculation environment can be used. There is always the question of what kinds of simplifications can be made while preserving the reliability of the results. As many simplifications as possible are usually done in the name of the effectiveness of the design process. Sometimes it would be better to invest resources in planning to get better and safer buildings. Yet, some simplifications must be done because real natural phenomena are too complicated to be solved by the known calculation resources of computers.

2.2 The properties of analysis programs

In the following the properties of analysis programs are discussed from the point of view of natural fire design.
The first question concerning an analysis program is how does it calculate structures in fire? This paper discusses the following three alternatives:

1) Calculation of isolated members where elevated temperatures only decrease the resistances of the members and joints.
2) As case 1) but using special methods to estimate the effects of elongations of members and stiffness of neighbouring structures in fire.
3) Nonlinear analysis with geometrical and material non-linearities with respect to elevated temperatures.

The first alternative is the basic level which all common programs can reach. The method is very quick and widely used. Theoretically it yields an exact solution if the structure is statically determined. Unfortunately all steel structures are not. If the structure is not statically determined, then thermal expansions exert extra forces on members and joints. In the beginning of a fire the beam between the columns is first subjected to compression due to the thermal extension of the beam, and after some time the beam loses its stiffness, compression changes to tension, and catenary action starts. The actions of joints between the columns and the beam change, correspondingly. The behaviour is more complex if the fire is real, meaning that the decay phase of the fire is present.
The second alternative can be used in manual analysis by applying a special method developed in [Yin and Wang, 2005a] and [Yin and Wang, 2005b]. This method can be used for a very accurate estimation of the catenary action and the transition temperature from compression to tension in many cases. It gives safe but not very accurate results for estimating the maximum compression of members. The application of this method requires extra programming and control of the analysis model by the user to fully utilize the method in this context.
Nevertheless, the calculation of nonlinear behaviour is the only accurate way to analyse structures in fire, as it also allows analyzing the decay phase of fire, which in some cases may be critical [Pada, 2011]. The related problems are that calculations take time and an advanced FEM program is needed. However, these kinds of programs are available and they get better all the time. Some problems with using two of these programs (SAFIR and VULCAN) for entire steel frames are reported in [Pada, 2011]. One solution for the long computing time proposed in [Pada, 2011] is to isolate, not the distinct members, but the relevant part of the entire building for the structural analysis. This typically requires some extra analysis runs, for example, to take into account stiffening systems located in non-isolated parts of the building.
Comparisons between and differences of these methods have been reported in literature. This paper mainly describes the process and the corresponding properties of programs.

The second question is whether the temperature of one member is constant in the longitudinal direction or across the cross section. It is often supposed that the temperature is constant along the entire length of the member. If the user thinks that the temperatures can vary a lot along the length, the member is easily divided into several parts. When the geometrical model is transformed into the analysis model, the real members are divided into several parts, and this option is typically implemented into the data transfer protocols. However, EN standards present factors that can be used conservatively to take into account the effect of non-uniform temperature along the member, thus enabling the use of only one finite element for the analysis of the member.

The direction of the cross section is more complicated. For example, if an I-profile is located over the fire, the lowest flange protects other parts from direct heat radiation by shading. Another very typical case is when there is a concrete slab on the top surface of the I-profile. The slab then protects the top flange so that its temperature will not be as high as that of other parts of the cross-section. EN standards give special shading factors to take into account different radiation effects in cross-sections. EN standards also give rules for estimating the uniform temperature of the cross-section using the well-known A_M/V ratio when all surfaces of the cross-section are not in fire. However, all the data needed for using the simplified rules of EN standards are required each time the steel temperatures are calculated.

If analysis of the non-uniform temperature of a cross-section is required, it can be done either using separate FEM programs (such as SAFIR, COMSOL, ABAQUS, etc) or by transferring the geometrical data of the member to the fire simulation program. It should be noted that the computational grids in FEM and fire simulation are typically totally different in size. If a grid size that can model parts of the cross section is used in the fire simulation, the needed calculation time easily becomes unreasonable. Missing data transfer protocols may also restrict the data content of the fire model. Some studies may be needed in some cases to investigate the effect of this simplification, using the uniform temperature across the cross-section. This is especially true for partly embedded columns in fire.

The third important question that must be solved in the planning of data transfer is where in the process are the temperatures of structures to be calculated from the gas temperature. A very rough method is just to take the highest gas temperature and assume that the temperature of the structure is the same. However there is a time lag so that it takes time for structures to reach the gas temperatures. In many natural fires the steel temperatures never reach the maximum gas temperatures. The three basic alternatives to calculate the temperatures of the structures are:

1) During the fire simulation. Then there are some risks related to determining output values because the temperatures must be output exactly at the surface of the member. The coordinates of the fire model are rounded to the calculation grid and it should be ensured that the output points are in the right places after the rounding. These problems with FDS are considered in [Heinisuo, Laasonen, 2007]. The proposed solution was that different parts of the members (e.g. flanges and webs) will be considered separately in the data transfer. Thus the rounding error can be minimised but it still exists and may cause problems. It should also be noted that fire simulation programs can analyse heat transfer inside the material entities in only one direction.
2) As part of the data transfer. The integration schedule of temperature can be programmed inside the data transformation but it is a little laborious because the information of the cross sections and materials must be available. However, this enables the use of a totally different less heavy FEM program (e.g. SAFIR) for the task. This system means extra data transfer into and out of this FEM program.
3) In the analysis program. This is the easiest way, but it requires that the analysis program can read the time-temperature curve from the fire simulation program output. Some programs can use only an ISO fire curve, which is useless when considering natural fires. All the data needed for the calculation of steel temperatures following EN standards are also required as input. These data indicate, for instance, how many surfaces are in fire, the shading factor, emissivity of surfaces, convection factors of surfaces, possible information on fire protection.

Figure 2 shows the three alternatives described above for transferring temperatures from fire simulation to structural analysis. Each beam must be assigned the nearest temperature. The assignment can be based on the coordinates or a separate coding system for output points.

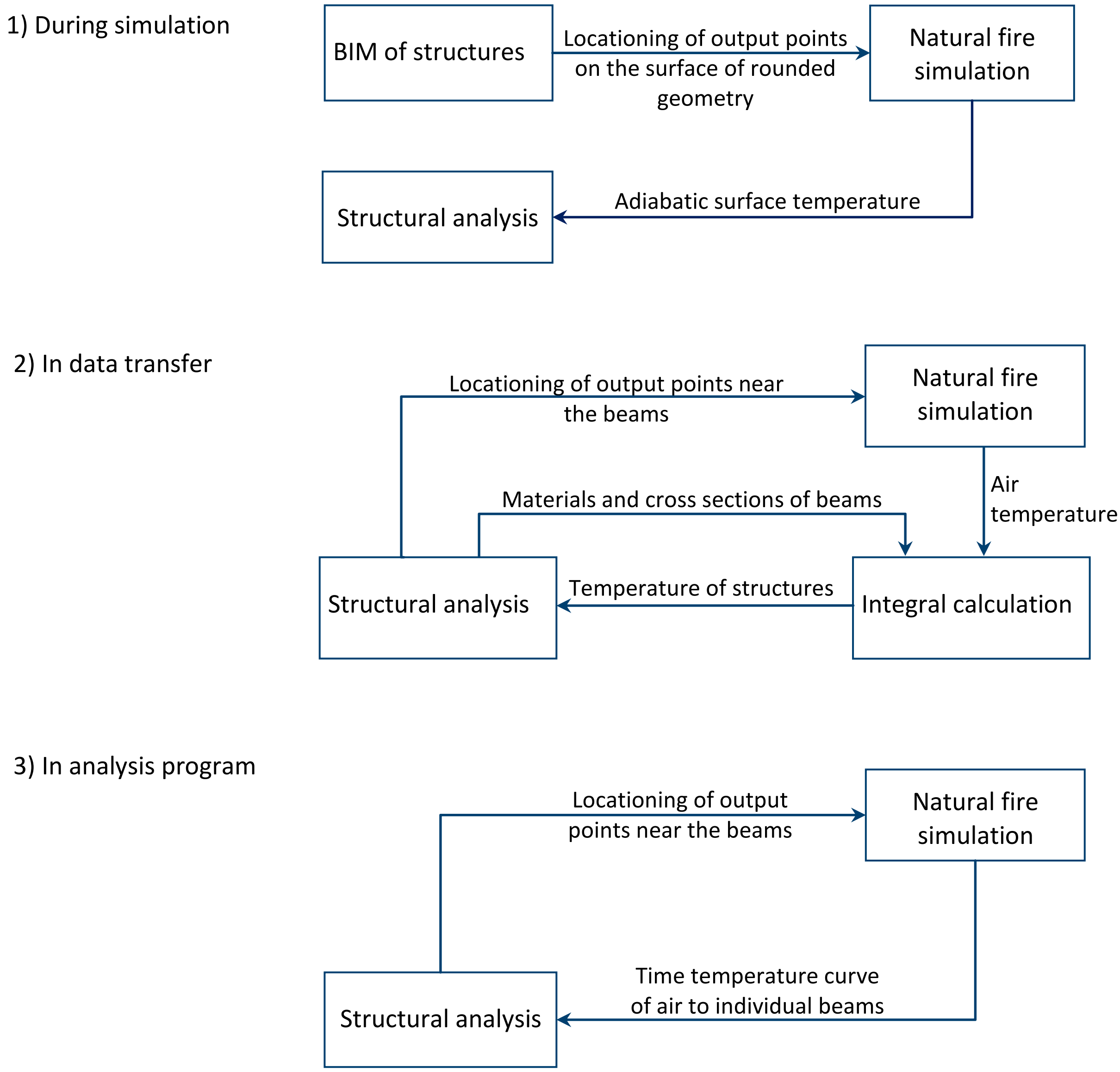

Figure 2: Three alternatives for transferring the temperature data to structures.

When considering the joints of steel structures, alternatives 1-2 can be used to define the temperatures of different parts of joints in fire. Alternative 3 can also be used for the first estimation, when using the component method of EN standards. Then extra control points should be located near the joints, for instance, near the bolt ends in the FDS model. The gas temperatures of these control points can be used for the temperatures of components of joints. The A_M/V ratio can be used to get more accurate temperatures of components of steel joints, for example, for end plates against concrete. Then, of course, the data to take this into account should be transferred from the BIM to the analysis model.

When calculating steel temperatures based on the gas temperatures near the structures, it is not necessary to take into account the noise of the gas temperature data. Steel members cannot follow these high frequency temperature changes and linearization of the gas temperature data can be done conservatively. This rule can be motivated based on a Fourier analysis [Heinsuo et al., 2008b]. It is also recommended [Pada, 2011] to do that to speed up the calculations of steel temperatures in practice. Likewise, the use of the time step of 5 s recommended in EN standards for the calculation of steel temperatures has been found very conservative [Hyvärinen, 2008]. Typically 30 s is a safe time step.

2.3 Methods to speed up calculation time

Even if the power of technical calculation is constantly increasing, in practical cases calculation time often limits simulation and analysis. There are several possibilities to tackle this obstacle. The main method to speed up calculation is the use of a coarser calculation mesh. The user must be careful in using this method because it may lead to uncertain results. In the following some other possibilities to reduce the turnaround time of the planning process are presented.

The simulation process produces separate temperature curves for every member, which may include several time steps per second. In a large building or in simulation covering a long time, the amount of data may cause a problem because the calculation of nonlinear temperature data is slow. Then, the amount of data can be limited by the following methods:

- Using only one finite element for one member, possible if factors of EN standards can be used. Requirements for cases where these factors can be used are given in EN standards.
- Using the same temperatures for as many members as possible. This speeds up the analysis considerably [Pada, 2011].
- Using a time step of 30 s for integration steps when calculating steel temperatures based on gas temperatures.
- Using linearization of gas temperatures.

The calculation time of the fire simulation is difficult to reduce. The best way is to distribute the calculation to as many processors as possible. Some other methods for quicker can also be used:

- If the space where the fire is located is large, it can be supposed that the amount of air does not limit the fire. Then only the hot area round the fire can be modeled and the borders of the area left open. The width of the hot area can be estimated by Alpert's method referred to e.g. in [Heinsuo et al., 2008b].
- In many cases the building is sprinklered. Instead of accurate nonlinear calculation of sprinklers, the fire load can be decreased. The lowering of the fire load must be evaluated by test calculations so that they output about the same results as the sprinklered case. The evaluated fire package can then be used in several simulations if the design variables are constant.
- Richardson's extrapolation to smaller grid size is widely used in analyses. However, extrapolation over the recommended grid size based on the resolution factor may produce erroneous results [Heinisuo et al., 2009].

2.4 Methods to speed up modeling

The basic idea is that no special BIM is needed but the normal planning process model suffices. This way repetitive modeling can be avoided. Before fire simulation, the geometrical model must be completed. In a fire simulation using the fluid mechanism, obstacles and fires have to be modeled as rectangular objects. Then not only the geometrical model but also the transformation should be planned before the calculation. This may be done by adding the mesh used in the fire simulation also to the geometrical model. Other information that must be added to the model is the fire packages which should be located at every critical point. Usually the highest temperatures of structures appear when they are met by flames. In addition, a fire burns better where more air is available. The most dangerous locations of fires are near open doors or windows.

If the used BIM includes only the bearing structures, the building parts limiting the burning area must be added to the model. In that phase the model can be simplified quickly.

- All details are not needed in the geometric model of the building. The main aim of the model is to limit the air space and confirm that there is no uncontrolled ventilation. Small details can be rounded to straight surfaces as will be done anyway in the transmission to the fire model.
- In a real fire windows will break when the temperature rises high enough. This can also be modeled in the fire simulation. A simplified solution is to leave all the windows open from the beginning. That can be assumed to be safe because the amount of air is maximal.
- The fire model can be assigned temperature dependent curves depicting how different materials behave in fire. If the fire packages are planned so that they can be assumed to include all the burning material, all other building parts can be considered inertia material in the fire model. This assumption may cause slightly higher output temperatures when, for example, a massive concrete wall does not absorb heat.

3 UTILIZATION

Practical examples of utilizing the method are presented e.g. by [Heinisuo et al., 2010]. The planning environment has been developed at Tampere University of Technology, and it has been used with some real buildings.

When simplifying methods are utilized in calculations, they have an effect on the end result. Simplifications should always lead to safer solutions. The magnitude of the effect on the end results of each simplification mentioned above are presented in Table 1.

Simplifying method	Condition for simplification
Calculation of temperature of structure	
• The use of gas temperature structures	If maximum is used
• Temperatures only decrease resistances of structures	If the structure is statically determined
• Estimate the effects of elongations	a separate program
• Temperature is constant across the cross section	OK
• Temperature is constant along the length	OK
Methods to speed up the analysis calculations	
• Using only one finite element for each member	If factors of EN can be used
• Using the same temperature for several rods	If maximum is used
• Reducing noise in time-temperature curves	OK
• Linearized time temperature curves	OK
Methods to speed up fire simulation calculations	
• Simulation of sprinklers is replaced by reduced fire load.	OK, EN rules are conservative
• Only the hot area around the fire is modeled	OK
• Richardson's extrapolation	If grid size smaller than allowed resolution factor

Table 1: Simplification of calculation.

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