SAFIR

Technical documentation

This document contains the technical documentation of the calculation method implemented in the numerical software SAFIR developed at the University of Liege for the simulation of building structures subjected to fire.

At present (23 February 2011),

- only the thermal part of SAFIR is considered in this document;
- this document is still under construction

This document is organized in the manner specified in the standard ISO/FDIS 16730:2008(E)

"*Fire safety engineering - Assessment, verification and validation of calculation methods*"

A Description of SAFIR

A.1 Purpose of SAFIR

A.1.1 Problem solved by SAFIR

The aim of SAFIR (thermal analysis) is to calculate the field of temperatures that develops in a building structure when this structure is subjected to a fire.

The temperature field is not uniform in the structure and varies during the course of the fire (transient situation).

Different materials may form the building structure such as steel, concrete, timber, gypsum, insulating materials or, in general, any material for which the user knows the required thermal properties.

The fire may be represented in different manners (temperature-time curves, imposed heat flux, local models) but its duration is in the order of magnitude of the duration of a building fire, i.e. some hours at maximum. Very long exposition (e.g. several days) to high temperatures is not in the field of application of SAFIR, essentially because the thermal properties embedded in SAFIR have not been developed to represent this situation.

2D as well as 3D structures can be analyzed.

The results are written in such a way that they can be used in a subsequent analysis performed by SAFIR in order to simulate the mechanical behavior of the structure (mechanical analysis).

A.1.2 Results of SAFIR

SAFIR provides the temperatures, in degree Celsius, at all the nodes that form the discretized structure, at all the time steps chosen by the user.

SAFIR can also, in some cases, give the average temperature for all the finite elements that form the discretized structure, at all the time steps chosen by the user.

SAFIR can also give the incremental temperature variation at all nodes that form the structure at all iterations of all time steps used for the calculation. This capability is mainly used for debugging a problem.

SAFIR can also give the incremental out of balance thermal forces at all nodes that form the structure at all iterations of all time steps used for the calculation. This capability is mainly used for debugging a problem.

A.1.3 Feasibility studies and justification statements

Justification statements

The determination of temperatures in structures subjected to fire is mainly undertaken in order to allow the determination of the mechanical behavior of structures subjected to fire. The mechanical behavior is indeed directly influenced by the loss of strength and stiffness as well as by the effects of thermal elongation in materials resulting from the temperature increase.

This knowledge of the temperature field is required when the mechanical behavior of the structure is determined by numerical models (see technical reference of the mechanical part of SAFIR), and also when the resistance of simple elements or assemblies is determined by simple calculation models.

Feasability

The determination of temperature fields in different types of structures subjected to various thermal loads by the finite element technique has been successfully undertaken for several decades already. Well established theories exist that describe the different physical phenomena that are involved. It is reasonable to believe that the same theories could be applied to structures subjected to fire provided that the particular characteristics of the exposure to a fire are correctly taken into account.

The feasibility of this type of approach has been demonstrated by previous software of this type having been developed and used (FIRES-T). The ambition that prevailed at the creation of SAFIR was to have a calculation method that has a wider field of application, hat allows a more user friendly utilization and that produces its results in a format that is appropriate for direct utilization in a subsequent mechanical analysis.

A.2 Theory

A.2.1 Underlying conceptual model

The underlying model is that in which heat is distributed in the structure essentially by conduction because most of construction elements are made of solid.

In some cases, this model is an approximation of more complex physical phenomena that take place. This is the case, for example,

- for the transmission of heat in mineral wool where conduction along individual fibers, radiation from fiber to fiber and convection in included air all play a role,
- for the expansion of intumescent paintings,
- for the charring of wood.

For such cases, the model of conduction is an approximation of reality and the thermal properties used in the conduction model have to be tuned in order to yield sufficiently correct temperatures in the underlying structure.

If a certain amount of evaporable water is contained in the materials, the energy consumed for the vaporization is taken into account in the model but the migration of the vapor with eventual re-condensation is not taken into account.

Some structures may comprise internal cavities in which no solid but gas is present. This is the case, for example, in internal cavities of hollow core slabs, for the gaps between H steel sections and plates of insulating material, for the interior of hollow steel sections or for the space between the two layers of gypsum plaster boards in steel studs or timber studs gypsum plaster walls. A model that describes the heat transfer by convection and radiation in these cavities is included in SAFIR. It is based on the following hypotheses:

- There is no heat transfer by conduction within the gas that is in the cavity.
- The specific heat of the gas in the cavity is neglected.
- The gas in the cavity is transparent to radiation (non participating media).

The model present in SAFIR cannot appropriately describe the temperature distribution in structural systems made of water filled steel tubes.

The model present in SAFIR for the evaluation of the temperature does not take into account the effects of the mechanical analysis (e.g. heat developed by plasticity, orthotropic character of the thermal properties induced by cracking in concrete, spalling) on the temperature distribution.

At the boundary of the structure, heat is exchanged with the environment (fire or ambient temperature conditions) by convection and radiation. In concave sections, with reentrant surfaces, the heat exchange between the different surfaces of the reentrant section is not considered. This is the case, for example, between the web and the internal part of the flange in a H steel section[1].

[1] Heat exchange is considered in internal parts of the sections that form closed cavities, as explained previously.

A.2.2 Theoretical basis of the phenomena and physical laws on which SAFIR is based

For conduction in the solids, heat exchange is based on Fourier equation. In a Cartesian system of coordinates, it is expressed by Eq. (1.1).

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q=c\rho\frac{\partial T}{\partial t} \tag{0.1}$$

where $\{x,y,z\}$ is the vector of Cartesian coordinates [m],
T is the temperature [K],
k is the thermal conductivity [W/mK],
Q is a term that accounts for internal generation of heat [W/m³],
ρ is the specific mass [kg/m³],
c is the specific heat [J/kgK],
t is time [s].

At the surface and in internal cavities, heat exchange is based on linear convection, see Eq. (1.2), and on the law of grey bodies, see Eq. (1.3), which means that the radiative flux does not depend on the wave length of electromagnetic waves.

$$\dot{h}_c = h\left(T_g - T_S\right) \tag{0.2}$$

where $\dot{h}_c$ is the convective heat flux between a gas and a solid [W/m²]
h is the coefficient of convection [W/m²K],
T_g is the temperature of the gas [K],
T_s is the temperature at the surface of the solid [K].

$$\dot{h}_r = \sigma\,\varepsilon\,T_S^4 \tag{0.3}$$

where $\dot{h}_r$ is the radiative heat flux emitted by a solid [W/m²]
σ is the Stefan-Boltzman constant [5.67×10^{-8} W/mK^4],
ε is the emissivity of the solid [-],
T_s is the temperature at the surface of the solid [K].

In internal cavities, the law of xxx is applied.

$$
\begin{aligned}
G_i &= \sum_j F_{ij} J_j \\
J_i &= \sigma \varepsilon_i T_i^4 + (1 - \varepsilon_i) G_i \\
Q_i &= \sigma \varepsilon_i T_i^4 - \varepsilon_i G_i
\end{aligned} \tag{0.4}
$$

where G_i is the radiative flux received by the surface i,

J_i is the radiative flux emitted by the surface i,

q_i is the net flux leaving the surface i,

F_{ij} is the view factor between surface *I* and *j*.

A. 3 Implementation of theory

- present the governing equations;
- describe the mathematical techniques, procedures and computational algorithms employed and provide references to them;

- identify all the assumptions embedded in the logic, taking into account limitations on the input parameters that are caused by the range of applicability of the calculation method;
- discuss the precision of the results obtained by important algorithms and, in the case of computer models, any dependence on particular computer capabilities;
- describe results of the sensitivity analyses;

A.3.1 Governing equations, mathematical techniques, procedures and computational algorithms

The temperature distribution is determined using the Finite Element (F.E.) technique.

The object in which the temperatures have to be determined is discretised by the user in a certain number of elementary surfaces (in 2D problems) or volumes (in 3D problems), each of them having simple shape; these elementary surfaces of volumes are the finite elements.

These elements are supported by points that are distributed by the user in the surface or volume to be analyzed; the points are the nodes. The nodes form the "summits" or the "corners" of the finite elements.

In SAFIR, linear elements are used, which means that the lines that form the boundaries of the elements, extending from a node to another, are straight lines and, also, the temperature variation that is assumed in each element varies linearly along each line that forms the boundaries of the elements.

Figure 1 shows three different discretisations made by a user of a rectangle to be analyzed as a 2D problem. In the first one, 105 triangular elements have been defined on the base of 72 nodes. In the second one, 75 quadrilateral elements have been defined on the base of 96 nodes. In the second one, 77 elements, some triangular and some quadrangular, have been defined on the base of 67 nodes. It is the responsibility of the user to choose, for the nodes, their number and their position and, for the elements, their number, their type and the nodes on which they are supported. It has to be understood that the result provided by SAFIR, i.e. the calculated temperature distribution, will be different in all three discretisations.

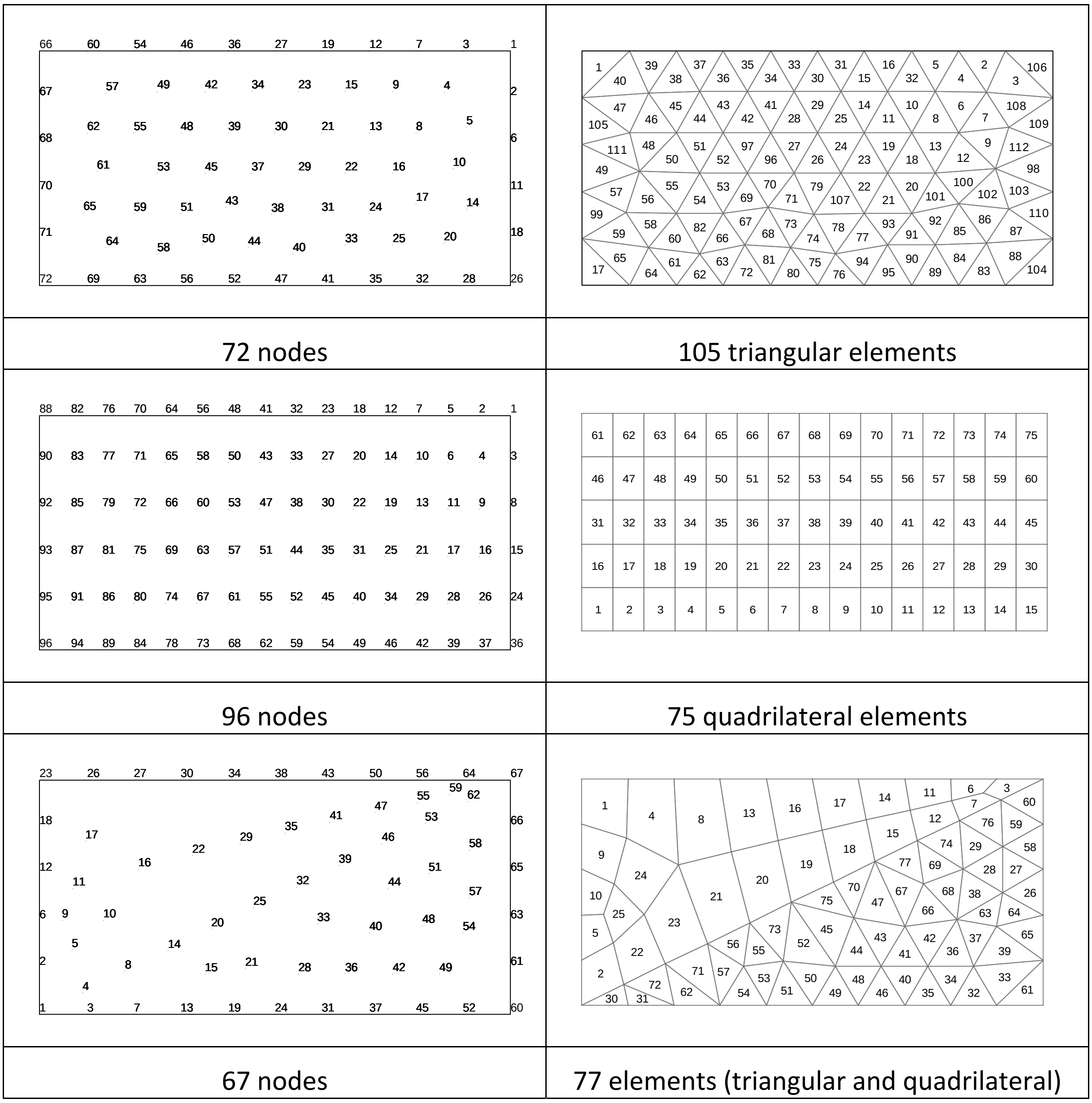
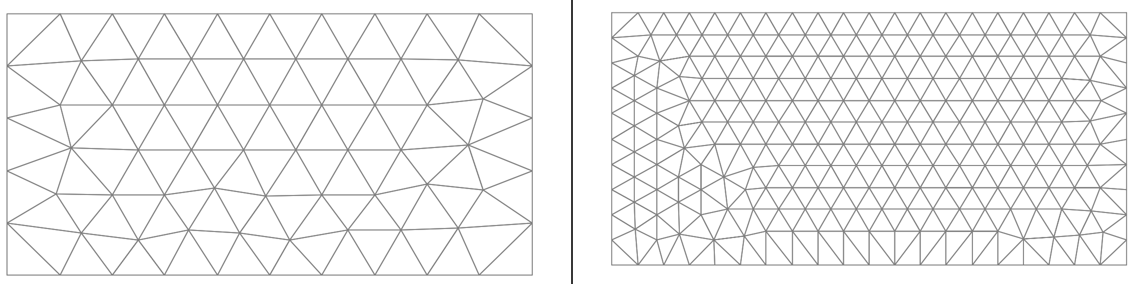


Figure 1: three different discretisations

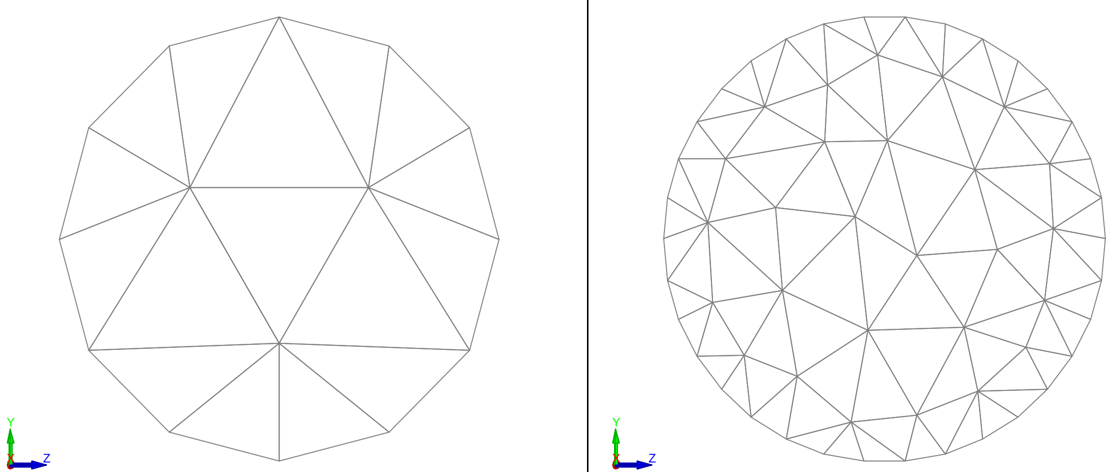
The user has also the responsibility to decide, through their size, of the number of elements used in the discretisation. Figure 2 shows the same rectangle discretised in each case with triangular elements, but the size of the elements on the right hand discretisation is approximately half of the size of the elements on the left hand discretisation leading to, approximately, four times the number of elements. The solution provided by SAFIR for each solution will also be different. The theory shows that the solution provided by SAFIR tends toward the true solution when the size of the elements tends toward 0. Of course, increasing the number of nodes and elements will increase the computation time required by SAFIR to calculate the solution.



105 elements	430 triangular elements

Figure 2: crude mesh and fine mesh

The difference in solution between both discretisations of Figure 2 is due to the different refinements of the mesh in the section but, in this case, the geometry of the boundaries of the section is represented exactly; the rectangle of the real section is also a rectangle in the discretised section. In other cases, the geometry is not made of straight lines and, because of the utilization of linear finite elements, the true geometry is approximated by a finite number of straight lines. The size, and hence the number, of the finite elements leads to a cruder or finer representation of the real geometry. Figure 3 illustrates the problem for the representation of the perimeter of a circle. In some situations, the approximation of curved lines or surfaces may occur inside the section, namely at the interface between two different materials. Example are the interface between a steel bar and the concrete in a reinforced concrete section or the interface between the root fillet of a laminated steel section and the concrete located in the chambers of the steel section for creating a composite steel-concrete section.



Circle approximated by 12 segments	Circle approximated by 34 segments

Figure 3: crude and fine representation of the boundary

A.2.1 Boundary conditions

Different boundary conditions can be applied at the borders of the structure.

A.2.1.1 Adiabatic boundary condition

A surface on which no condition at all is prescribed will behave as an adiabatic boundary. This means that no heat flux will travel through this boundary. As a consequence, the isotherms in the structure will be perpendicular to this boundary. Such a condition may be used to represent a geometrical axis of symmetry in the problem to be solved or a boundary of the structure that is in contact with a lightweight material.

A.2.1.2 Imposed nodal temperature

The evolution of the temperature at nodes located on the boundaries of the structure can be imposed by the user (see the **BLOCK** command). This is normally used only for benchmarking in comparisons with other software performed on academic case studies.

Note: the temperature of nodes located inside the structure, as opposed to nodes located on the boundaries of the structure, can also be imposed by the user with **BLOCK** command.

B Assessment of the calculation method

B.1 Predictive capabilities

For simplicity reasons, the content of this section B.1 has been put in Annex B.1. This annex is contained in a document called "Technical Reference of SAFIR - Annex B1.docx".

Terms and definitions

Discretisation

The process by which the user represents to structure (that, by nature, is a continuous object) into a model made of a finite number of nodes and elements.

Iteration

Because the thermal problem to be solved is non linear, SAFIR cannot calculate the temperature directly at a given time step as a function of the temperatures that were calculated at the previous time step. In order to calculate the temperature at a given time step, SAFIR has to perform several trial and error calculations during which the temperatures are progressively refined. Each of these trials and errors is called an iteration.

Time step

A particular time during the course of the fire fat which SAFIR will calculate the temperatures (times steps used for the calculation). The time steps are chosen by the user.

User

The person who collects the input data for the problem to be solved, who creates a model representing the problem (the fire and the structure) that can be analyzed by SAFIR and who interprets the results provided by SAFIR.

List of symbols

c specific heat [J/kgK]

h coefficient of convection [W/m²K]

$\dot{h}_c$ convective heat flux between a gas and a solid [W/m²]

k thermal conductivity [W/mK]

t time [s]

Q internal generation of heat [W/m³]

T temperature [K]

T_g temperature of the gas [K]

T_s temperature at the surface of the solid [K]

ρ specific mass [kg/m³]