A tool to design steel elements submitted to compartment fires - *OZone* V2
Part 2: Methodology and application

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Abstract

The methodology implemented in the tool *OZone* V2 to design steel elements submitted to compartment fires is presented. Input needed to define a fire compartment are first quoted. The procedure to define the design fire is then explained. This procedure enables to take into account the benefits of active measures on the fire safety. The combined use of a two and a one zone model is then presented. A particular attention is given to the criteria of choice of the model and to the different scenarios that can occur. The calculation of steel element temperature is then explained. The proposed procedure takes into account the localised effect of a fire with the help of Hasemi’s model. The fire resistance is then calculated with the EUROCODE 3 methods. An application is finally presented.

*Keywords*: compartment fire, zone model, localised fire, design fire, fire scenario, steel elements.

Notation

- **1ZM**: One zone model
- **2ZM**: Two zone model

- $\varepsilon^*$: Relative emissivity of steel-gas interface (0.50).
- $\gamma$: Partial safety factor
- $\gamma_{q,1}$: Partial safety factor associated with the floor area of the compartment
- $\gamma_{q,2}$: Partial safety factor associated with the danger of fire activation
- $\gamma_{n,i}$: $i= 1$ to 10; partial safety factor associated with the active measures
- $\rho_\infty$: [kg/m$^3$] Density of air
- $\sigma$: Constant of Stefan-Boltzman (5.67 $10^8$)

- $a_1$: Fraction of the height of the compartment
- $a_2$: Fraction of the floor area of the compartment
- $A_f$: [m$^2$] Floor area of a compartment
- $A_{fi}$: [m$^2$] Horizontal burning area of fuel
\[ A_{fi, \text{max}} \] \text{[m}^2\text{]} \quad \text{maximum horizontal burning area of fuel}

\[ h \] \text{[W/mK]} \quad \text{coefficient of convection (25 W/mK)}

\[ H \] \text{[m]} \quad \text{height of the compartment}

\[ H_{c, \text{eff}} \] \text{[J/kg]} \quad \text{effective combustion heat of fuel}

\[ H_{c, \text{net}} \] \text{[J/kg]} \quad \text{complete combustion heat of fuel}

\[ m \] \quad \text{combustion efficiency factor}

\[ m_f \] \text{[kg]} \quad \text{total mass of fuel}

\[ m_f \] \text{[kg/s]} \quad \text{pyrolysis rate}

\[ q'' \] \text{[W/m}^2\text{]} \quad \text{heat flux to the boundaries of a steel element}

\[ q_f \] \text{[J/m}^2\text{]} \quad \text{fire load density (per unit floor area of compartment)}

\[ q_{f,k} \] \text{[J/m}^2\text{]} \quad \text{characteristic fire load density}

\[ q_{f,k,\text{eff}} \] \text{[J/m}^2\text{]} \quad \text{effective characteristic fire load density}

\[ q_{f,\text{net}} \] \text{[J/m}^2\text{]} \quad \text{net characteristic fire load density}

\[ q_{f,d} \] \text{[J/m}^2\text{]} \quad \text{design fire load density}

\[ q_{net} \] \text{[W/m}^2\text{]} \quad \text{net heat flux at the boundaries of a steel profile}

\[ RHR \] \text{[W]} \quad \text{rate of heat release}

\[ RHR_{\text{eff}} \] \text{[W/m}^2\text{]} \quad \text{effective rate of heat release per unit floor area of compartment}

\[ t \] \text{[s]} \quad \text{time}

\[ t_{\text{a}} \] \text{[s]} \quad \text{time at which RHR equal 1MW (defining the rising phase of a fire)}

\[ T_{\text{FL}} \] \text{[K]} \quad \text{temperature at which flashover occurs}

\[ T_g \] \text{[K]} \quad \text{temperature of the gas (1ZM)}

\[ T_{\text{loc}} \] \text{[K]} \quad \text{fictive temperature for localised effect of fire}

\[ T \] \text{[K]} \quad \text{temperature of the section}

\[ T_U & T_L \] \text{[K]} \quad \text{temperatures of the gas of, respectively, the upper and lower layer (2ZM)}

\[ T_z \] \text{[K]} \quad \text{temperature of a zone}

\[ Z_q \] \text{[m]} \quad \text{height of fuel}

\[ Z_s \] \text{[m]} \quad \text{altitude of zones interface}

1 Introduction

Prescriptive codes for structural fire resistance tend to be replaced by performance based codes. Yet, particularly in Europe, structural engineers are not used to model fires and their effect on structures. The tool presented in this paper has thus been elaborated to help them to design structural steel elements submitted to compartments fires.

Basic knowledge and understanding has been gained over the last decades by specialists in fire modelling. Other specialists in the structural behaviour of buildings submitted to the fire have also made progress in their field. Too often yet, very little communication took part between these two fields of fire safety engineering; whereas the former used to think of the structural problem only in terms of a critical temperature of, say, 540°C, the latter used to represent the fire by a single nominal time-temperature curve, either the ISO 834 or the ASTM E119 curve.

Most of the knowledge is thus present allowing to make a real engineering analysis of the structural aspects related to fire safety in buildings. This analysis requires the determination of the fire development in the compartment, then of the temperatures in the structural elements and, finally, of their mechanical behaviour. This knowledge was yet disseminated and it was not straightforward for a single individual to integrate all these notions for use in a practical, although simple application.

Ozone V2 has been developed as a practical design tool to realise a performance based analysis of the behaviour of simple steel elements in a compartment fire situation. Some particular new features have been introduced, the most significant being that the user has not
to make a predetermined choice as to the description of the situation of the fire in the compartment: one zone or two zone model? The model is able to consider the initial phase of the fire as a localized fire with a two zone development and, under certain circumstances, to switch later automatically to a one zone description if required.

The aim of this paper is to present the methodology used in this tool and to show an example of application.

2 Overview of the methodology

The methodology of the design can be divided in 6 main steps that will be described in detail in the next sections. The steps are:

- 1 description of the compartment.
- 2 definition of design fire.
- 3 calculation of the temperatures in the compartment.
- 4 a. definition of the thermal and mechanical section properties, of the thermal properties of the insulation material if the section is protected and of the thermal boundary conditions.
  b. calculation of the temperature of steel elements, taking into account if necessary, the localised effect of the fire with the help of Hasemi's model.
- 5 a. definition of the dimensions, the solicitations, and static boundary conditions of the member.
  b. calculation of the fire resistance of the steel element.
- 6 acceptance or not of the fire resistance obtained in step 5. If the fire resistance is not accepted, the section or the thermal resistance of the insulation has to be increased and the process must be restarted from step 4.

These steps are described in the subsequent sections of this paper.

3 Compartment

The compartment is described by:

- Its plan and elevation dimensions.
- The partition characteristics: layers thickness and thermal properties of materials.
- The size and position of openings: vertical and horizontal openings and forced vents can be modelled.

4 Design fires

The basic input to define the fire are the rate of heat release $RHR(t)$ [W], the pyrolysis rate $m_{fi}(t)$ [kg/s] and the fire area $A_{fi}(t)$ in function of time. They are defined in [3].

This section presents the definition of design fire proposed as standard options in the software. In this context, the expression 'Design fire' refers to the definition of the fire source development ($RHR(t)$ mainly) and not to temperature time curves. The procedure is based on the "Natural Fire Safety Concept" method. The bases of this method are first presented.

4.1 Probabilistic basis of the method "Natural Fire Safety Concept"

The procedure proposed to define the design fires is a semi probabilistic approach developed in the research project "Competitive Steel Structures through Natural Fire Safety Concept" [1]. From pure probabilistic calculations, some partial safety factors $\gamma$ on the fire load have been evaluated. The design fire load density is obtained by multiplying the characteristic fire load by the partial safety factors. The probability of structural failure due to a fire during the whole life of a structure, $p_f$, can be obtained from the theorem of conditional
probabilities given in Eq. (1). The probability \( p_t \) is acceptable if it is lower than a target value, \( p_t \).

\[
p_t (\text{failure from a fire}) = p_{f} (\text{getting a fully developed fire}) \times p_{f,fi} (\text{failure in case of a fire}) \leq p_t (\text{target probability})
\]  
(1)

The methodology used was to
a) collect statistics,
b) from these statistics, deduce probabilities that:
   - a fire starts
   - the occupants fail in stopping the fire
   - the automatic active measures to extinguish the fire fail in stopping the fire
   - the fire brigade does not succeed in stopping the fire
c) from these probabilities, calculate partial safety factor with the method proposed in Annex A of ENV 1991-1 [4]

The design fire load density is given by Eq. (4) of section 4.2.

### 4.2 Construction of the design fire

The construction of the design fire implies to build the rate of heat release curve (Figure 1), the mass loss rate curve (Figure 2) and the fire area curve. The following parameters are needed:

**Net versus effective parameters**

When talking about combustion heat, fire load or rate of heat release, it is important to know whether the combustion efficiency is taken into account in the value or not. The combustion efficiency represents the fact that a unit mass of fuel releases less energy in real fires than in an oxygen bomb calorimeter. A net value of a parameter is related to the estimation of the parameter with the net combustion heat (evaluated in bomb calorimeter conditions) while an effective value is related to the estimation of the parameter with the effective combustion heat (expected to occur in real fire conditions). For example, \( q_{f, k, \text{net}} \), the net characteristic fire load density is linked to \( q_{f, k, \text{eff}} \), the effective characteristic fire load density, by Eq (2). \( m \) is the combustion efficiency factor (\( m \) factor).

\[
q_{f, k, \text{eff}} = m \times q_{f, k, \text{net}} \tag{2}
\]

**Fire Load Density - \( q_f \)**

The characteristic fire load density \( q_{f, k} \) considered in the NFSC Design Fire is the 80% fractile of the fire load distribution obtained by survey in real compartments. Data are available for different types of occupancies of compartments. In order to obtain these data, the mass of all types of combustible present in compartments has been measured. Eq. (3) gives the net fire load density.

\[
q_{f, net} = \frac{1}{A_f} \sum_i H_{cnet,i} M_i \tag{3}
\]

**Design Fire Load Density - \( q_{f,d} \)**

The design fire load density \( q_{f,d} \) is given by Eq. (4).

\[
q_{f,d} = \gamma_1 \gamma_2 \prod_i \gamma_{nj} m \times q_{f, k, \text{net}} \tag{4}
\]
The influence of the compartment area on the probability of starting of a fire is taken into account by $\gamma_{q1}$ factor. The influence of the danger of fire activation on the probability of fire start is taken into account by $\gamma_{q2}$ factor. The danger of fire activation is related to the type of occupancy of the building. The influence of active measures are taken into account by $\gamma_{a,i}$ factors. The active measures are: Automatic Water Extinguishing System; Automatic Fire Detection by Heat; Automatic Fire Detection by Smoke; Automatic Alarm Transmission to Fire Brigade; Work Fire Brigade; Off Site Fire Brigade.

The value of the different partial safety factors can be found in [5] for different types of building occupancy and fire safety measure.

**Fire Growth Rate - $t_a$**

The rising phase of fire is assumed to follow the $t^2$ evolution, characterised by the fire growth rate $t_a$, which is the time at which the fire area $A_{fi}$ has grown to a value leading to an effective rate of heat release of 1MW. The rate of heat release during the growth phase is given by Eq. (5).

$$RHR(t) = 10^6 \left( \frac{t}{t_a} \right)^2$$

**Rate of Heat Release per Unit Area of Fire - $RHR_{f,eff}$**

The effective rate of heat release per unit area of fire $RHR_{f,eff}$ is the maximum quantity of energy which can be released by unit area of fire in steady state situation without control by the ventilation. This quantity, $RHR_{f,eff}$, is given in the literature for different types of compartment occupancies. The values of $RHR_{f,eff}$ are for real fires and take into account the incomplete combustion. This quantity is assumed to be constant during the fire.

**Maximum Fire Area - $A_{fi,max}$**

The maximum fire area is the maximum burning area of fuel, i.e. the area of floor on which combustible is present.

**Steady state phase of the fire development**

The steady state phase is reached when all the fuel burns. It is the maximum rate of heat release that can be encountered for a given design fire. This phase may stand during a certain amount of time or may not exist if the decreasing phase begins during rising phase.

$$RHR(t) = A_{fi,max} RHR_{f,eff}$$

**Decreasing phase**

The decreasing phase of the fire begins when 70% of the design fire load is consumed. This phase is considered to be linear.

**Pyrolisis rate**

The pyrolisis rate is given at any time by Eq. (7)

$$m_f(t) = \frac{RHR(t)}{H_{eff}} = \frac{RHR(t)}{mH_{net}}$$

**Fire area**

The fire area is given at any time by Eq. (8)
The design fire curves can be built as shown on Figure 1 and Figure 2.

\[ A_f(t) = \frac{RHR(t)}{RHR_{f, eff}} \]  

(8)

**Design fire curves**

The design fire curves can be built as shown on Figure 1 and Figure 2.

4.3 Comments

A) With the proposed procedure, the rate of heat release curve is first built; the pyrolisis rate curve and the fire area curve are then deduced from the rate of heat release curve. This is due to the fact that fire safety scientists and engineers talk usually about fire sources in terms of energy, and thus data are available in terms of energy. A more physical approach would be to consider first the quantity of fuel that pyrolises and, from that, deduce the energy release.

Because the parameters used to define the fire are either effective parameters \((t_a, RHR)\) or either net parameters \((q_f)\), modifying the combustion efficiency in the design procedure will not change the rate of heat release curve during the rising and the steady state phases but will modify the design fire load and thus modify the fire duration. It will also modify the rate of mass loss curve. For example, when decreasing the \(m\) factor for a constant energy release rate, the fire duration will be decreased and the rate of mass loss will be increased. The physical meaning of this is the following: to release the same quantity of energy, more fuel is needed if the combustion efficiency is lower.

B) The "extended fire duration" combustion model is recommended for a design procedure. If there is a lack of oxygen in the compartment, the rate of heat release will be controlled by the ventilation and the fire duration will be extended so that all the energy of the fuel will finally be released inside the compartment [3]. The strategy of calculation may also influence these input as explained in section 5.3.

5 Gas temperature

The evaluation of the gas temperature in the compartment is made by the zone model described in [3]. Inputs are described in the two previous sections. The purpose of this section is to explain the strategy of the calculation, i.e. when the 2ZM and when the 1ZM are to be used, what are the criteria to be adopted to decide which model has to be applied, when and how the input rate of heat release has to be modified. Eventually the different scenarios that may be encountered are presented.

5.1 Application field of two and one zone models

Two zone and one zone models are based on different hypotheses and one can not say that there is a better model than the other. Indeed they correspond to different types of fires or
different stages of the same fire. They simply have different application domains and in fact they are complementing each other. When modelling a fire in a given compartment, it is important to know whether a two zone model or a one zone model is best appropriate.

A first important remark has to be made on the fire load distribution. The fire load can be considered to be uniformly distributed if the real combustible material is present more or less on the whole floor surface of the fire compartment and when the real fire load density (quantity of fuel per floor area) is more or less uniform. By opposition, the fire load is localised if the combustible material is concentrated on a quite small surface compared to the floor area, the rest of the floor area being free of fuel.

Uniformly distributed fire load

Fire ignitions are in most cases localised and therefore a fire remains localised during a certain amount of time. If temperatures are sufficiently high to induce spontaneous ignition of all the combustible present in the compartment, a fully engulfed fire occurs. Generally two zone models are valid in case of localised fires or pre-flashover fires and one zone models are valid in case of fully engulfed fires or post-flashover fires.

If the thickness of the lower layer is small compared to the height of the compartment, the two zone assumption is no longer applicable and a one zone model is more appropriate.

Finally, if the fire area is large compared to the floor area, the one zone model assumption is better than the two zone one.

These considerations imply that to model fires in a compartment with uniformly distributed fire load, a two zone model is well adapted for the first stages of the fire and then a one zone model will be a better assumption if some conditions on temperatures, fire area and smoke layer thickness are encountered.

Localised fire load

In case of localised fire load, when the temperature of the upper layer is sufficiently high to ignite the fuel by radiation, the complete fuel starts to burn and the rate of heat release is modified. In this case the fire remains localised and two different zones remain and a two zone model is thus still appropriate. In this case a one zone model can be more appropriate only if the thickness of the upper layer is large compared to the height of the compartment.

5.2 Choice of the model

In many cases, it is difficult to know a priori whether a fire will remain localised during its entire course or whether flashover will happen, and, in general, to know whether a two or a one zone model is more appropriated.

An automatic strategy is proposed to determine which model has to be used. With this strategy, the simulation always begins with the two zone model assumption and if one of the described conditions is encountered, the simulation will switch from the two zone model to the one zone model and/or will modify the mass and energy released by the fire.

The modifications of the main variables and of the basic equations when the switch to the one zone model occurs are presented in [3]. The consequences of flashover on the fire source model and the criteria of transition from two to one zone are discussed in sections 5.3 and 5.4 hereafter.

5.3 Fully developed fire

If a fire is modelled by the plain curve of Figure 3, the growing phase, represented here by a $t^2$ curve, is reaching a maximum at the time at which all the fire area has been ignited. If the fuel ignition happens only by flame spread, the maximum is reached without modification of the initial $t^2$ curve. If the temperature of hot gases of the upper layer of a fire reaches a
sufficiently high level (in the range 500°C to 600°C), the radiative flux from the hot gas to the non burning combustible materials can be as high as to ignite the fuel. At this moment there is a very fast increase of the energy release rate. This phenomenon is called flashover. This modification is made by modifying the initial rate of heat release curve as indicated by the dotted line in Figure 3. At the flashover time, the input RHR curve is abandoned and RHR goes to its maximum value equal to the maximum fire area multiplied by the rate of heat release density $RHR_f$.

![Figure 3 Modification of RHR(t) in case of flashover.](image)

If the gases in contact with the fuel reach a temperature of about 300°C, the fuel also ignites and the rate of heat release increases as stated for the flashover phenomena.

The decreasing phase, assumed to be linear, begins when 70% of the design fire load is consumed.

### 5.4 Criteria of transition from two to one zone model and/or of modification of the input of energy

The criteria of transition from two to one zone and/or of modification of the fire source are:

- **Criterion 1 (C1) :** $T_U > T_{FL}$
  High temperature of the upper layer gases, composed of combustion products and entrained air, leads to a flashover. All the fuel in the compartment is ignited by radiative flux from the upper layer.

- **Criterion 2 (C2) :** $Z_s < Z_q$ and $T_Z > T_{Ignition}$
  If the gases in contact with the fuel have a higher temperature than the ignition temperature of fuel ($T_{Ignition}$), the propagation of fire to all the combustible of the compartment will occur by convective ignition. The gases in contact (at temperature $T_Z$) can either belong to the lower layer of a two zone, the upper layer (if the decrease of the interface height ($Z_s$) leads to put combustible in the smoke layer - $Z_q$ is the maximum height of the combustible material) or the unique zone of one zone models.

- **Criterion 3 (C3) :** $Z_s < a_f H$
  The interface height goes down and leads to a very small lower layer thickness, which is not representative of two zone phenomenon.
- Criterion 4 (C4): $A_{fi} > a_2 A_f$

  The fire area is too high compared to the floor surface of the compartment to consider a localised fire.

Criteria 1 and 2 lead necessarily to a modification of the rate of heat release as specified in §5.3. If the fire load is localised the simulation will continue using a 2ZM and if the fire load is uniformly distributed, a 1ZM will be considered. If one of the criteria C3 or C4 is fulfilled, the code will switch to a one zone model but the RHR will not be modified, except if criterion C1 or C2 happens simultaneously. Table 1 and Figure 4 summarise the four criteria.

The proposed values of $T_{fl}$, $T_{ignition}$, $a_1$ and $a_2$ are given in Table 2.

### Table 1 Summary of transition criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Localised $q_f$</td>
<td>Distributed $q_f$</td>
</tr>
<tr>
<td>C1: $T_U &gt; T_{fl}$</td>
<td>$A_{fi} = A_{fi,max}$</td>
</tr>
<tr>
<td>C2: $Z_s &lt; H_q$ and $T_U &gt; T_{ignition}$ (2ZM) or $Z_s &gt; H_q$ and $T_L &gt; T_{ignition}$ (2ZM) or $T &gt; T_{ignition}$ (1ZM)</td>
<td>$A_{fi} = A_{fi,max}$</td>
</tr>
<tr>
<td>C3: $Z_s &lt; a_1 H$</td>
<td>1ZM</td>
</tr>
<tr>
<td>C4: $A_{fi} &gt; a_2 A_f$</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 2 Parameter value of transition criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>$T_{fl} = 500^\circ C$</td>
</tr>
<tr>
<td>C2</td>
<td>$T_{ignition} = 300^\circ C$</td>
</tr>
<tr>
<td>C3</td>
<td>$a_1 = 0.2$</td>
</tr>
<tr>
<td>C4</td>
<td>$a_2 = 0.25$</td>
</tr>
</tbody>
</table>
5.5 Fire scenarios

During the course of a simulation, the different criteria may be encountered or not. Eight different possibilities exist: Five if the fire load is localised, Three if the fire load is uniformly distributed.

Localised fire load:

- SCENARIO 1 - No criterion is encountered, the model will remain with two zones and the RHR curve will not be modified until the end of the fire.
- SCENARIO 2 - Criterion C1 or C2 is first encountered, leading to a RHR modification. Criterion C3 is not encountered, the model remains a two zones one.
- SCENARIO 3 - Criterion C1 or C2 is first encountered, leading to a RHR modification. Criterion C3 is encountered, the model switches from a two zones to a one zone.
- SCENARIO 4 - Criterion C3 is first encountered, the model switches from a two zones to a one zone. The criteria C1 and C2 are not encountered, leading to no RHR modification.
- **SCENARIO 5** - Criterion C3 is first encountered, the model switches from a two zones to a one zone. Criterion C1 or C2 is then encountered, leading to a RHR modification.

*Uniformly distributed fire load:*

- **SCENARIO 6** - Criterion C1 or C2 is encountered, leading to a RHR modification and a simultaneous switch from a two zones to a one zone model.
- **SCENARIO 7** - Criterion C3 or C4 is first encountered, the model switches from a two zones to a one zone. The criterion C1 and C2 are not encountered, leading to no RHR modification.
- **SCENARIO 8** - Criterion C3 or C4 is first encountered, the model switches from a two zones to a one zone. Criterion C1 or C2 is then encountered, leading to a RHR modification.

Figure 5 shows the organisation chart of the different scenarios a simulation can follow.

As the definition of the limit between uniformly and localised fire load is based on the criterion C4, it is obvious that criterion C4 is never encountered in case of localised fire load. For the same reason, in case of uniformly distributed fire load, criteria C4 will undoubtedly be fulfilled and therefore a simulation with uniformly distributed fire load will always switch to one zone model.

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**Figure 5 Organization chart of the combination strategy**

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**6 Heating of steel profile.**

The upper zone temperature which is calculated in a two zone fire situation can be considered as the average value of the temperature field in the gas of the upper layer. In fact, the thermal impact of a localised fire can be much more severe on structural elements located in the vicinity of the flames than the impact coming from the air at the average temperature. As a consequence, if the failure of the structural elements located close to a fire may be critical for the stability of the whole structure, then the average temperature is no more sufficient and the localised effect of the fire must be taken into account.

A first solution to model the local effect of a fire can be found in the correlation formula proposed by Alpert [7] to calculate the maximum gas temperature in the ceiling jet flow.
which forms when a vertical buoyant fire plume impinges on a horizontal ceiling and the gases spread laterally. As indicated by the title of Alpert's publication, his work was done with the objective of predicting response times of detectors and not the structural behaviour of the structure. Whereas the air temperature is a good indication for the response time of a detector, the thermal solicitation of a structure is not only influenced by the temperature of the air flowing on its surface but also, via radiation, by the fire itself. It is therefore preferable to make direct measurements of the heat flux received by the surface if the temperature of a structure has to be calculated. This is the kind of measurements made by Hasemi et al. ([8], [9], [10], [11]) in Japan.

Hasemi has proposed an empirical model based on these tests. Franssen et al. ([12], [13], [14]) improved slightly the original model in order to have a better fit with the original tests. Franssen also compared the modified model to four full scale tests and found reasonable agreement [12].

Myllymäki & Kokkala [15] made 10 additional tests, compared the results to calculations with the improved model and found that the improved model gave safe estimation of the tests results.

The combination of the local and the global effect of a fire on a steel element is shown on Figure 6.

The improved model is implemented in the code as formulated in [12].

![Figure 6 combination of localised fire model and zone model for thermal impact on steel beam](image)

The heat flux to the element \( q'' \) is given by the Hasemi's model in function of the heat released by the fire, the diameter of the fire and of the relative position of the steel element and the fire.
The net heat flux at the boundaries of a steel profile \( q_{\text{net}} \), taking into account the flux lost due to the temperature of the section, is given by Eq. (9).

\[
q_{\text{net}} = q'' - h (T_s - 293) - \sigma \epsilon \left( T_s^4 - 293^4 \right)
\]  

(9)

It is possible to deduce a fictive local temperature \( T_{\text{loc}} \) that has the same effect on steel elements as the net heat flux calculated with this method. It is indeed the temperature of steel profile with a very high massivity. This steel profile has a temperature which is very close to the gas temperature, thus we have: \( T_{\text{loc}} = T_g \). \( T_{\text{loc}} \) is then obtained by solving Eq. (10)

\[
q'' - h (T_{\text{loc}} - 293) - \sigma \epsilon \left( T_{\text{loc}}^4 - 293^4 \right) = 0
\]  

(10)

6.1 Heating

The heating of unprotected or protected steel profile is calculated with the ENV1993-1-2 methods. The gas temperature is either the upper zone temperature, the fictive local temperature obtained by Hasemi’s method or the maximum of these two temperatures.

7 Fire Resistance

The fire resistance of members is determined based on the assumptions stated in ENV 1993-1-2, § 2.4.4 - Member analysis [16] using Eq. (11):

\[
E_{\text{fi,d}} \leq R_{\text{fi,d,t}}
\]  

(11)

where:

- \( E_{\text{fi,d}} \) is the design effect of actions for the fire situation, determined in accordance with ENV 1991-2-2;
- \( R_{\text{fi,d,t}} \) is the corresponding design resistance at elevated temperatures.

The calculation of fire resistance is implemented for:
- Tension members (ENV 1993-1-2, § 4.2.3.1)
- Compression members with Class 1, Class 2 or Class 3 cross-section (ENV 1993-1-2, § 4.2.3.2)
- Beams with Class 1, Class 2 or Class 3 cross-section (ENV 1993-1-2, § 4.2.3.3 and 4.2.3.4)

The fire resistance is the time at which Eq. (11) becomes unsatisfied.

8 Application

An academic example of application of this tool is presented in this section. The fire resistance of a steel beam which supports a non collaborating concrete slab in a compartment is estimated in case of an unprotected and a protected steel section.

The data are:

- The compartment is used as a library.
- The square floor is 5m on 5m wide. The height is 3m. (inner dimension)
- All partitions are made of normal weight concrete (unit mass: 2300kg/m³; Conductivity: 2W/mK; specific heat: 900J/kgK) and are 10cm thick.
- There are two openings, one door (width : 1m; height: 2m) in first wall and one window (sill at 1m; soffit at 2m; width: 3m) in the third wall.
- The beam is a IPE400. Steel S355.
- The beam is simply supported from the middle of wall one to the middle of wall three and the load is uniformly distributed.
- The design bending moment at mid span is 100 kNm.
- The protection material is sprayed vermiculite (unit mass: 350 kg/m³; conductivity: 0.12 W/mK; specific heat: 1200 J/kgK)
Step 1: Define the compartment
The compartment is defined: internal dimensions, openings positions and sizes and partitions characteristics.

Step 2: Define the design fire
The suggested value of the NFSC method for a library are:
- Fire load uniformly distributed with a characteristic value $q_{f,k} = 1824 \text{ MJ/m}^2$
- $H_{c,net} = 17.5 \text{ MJ/kg}; m = 0.8$
- The fire growth rate is fast (1MW is released by the fire after 150 s)
- The maximum rate of heat release density is 500 kW/m$^2$.
- The partial safety factor which consider the benefits of the automatic fire detection by heat is $\gamma_{n,3} = 0.87$
- The partial safety factor which consider the benefits of off site fire brigade is $\gamma_{n,7} = 0.78$
- The fire risk area is equal to 25m$^2$ thus $\gamma_{q,1} = 1.12$
- The danger of fire activation is medium thus $\gamma_{q,2} = 1$
- The design fire load density is then calculated with Eq. (4), giving:
  $$q_{f,d} = 1109 \text{ MJ/m}^2$$

The rate of heat release data curve is build automatically as shown on Figure 8 (RHR data curve).

Step 3: Run the compartment fire model
The main output are the rate of heat release curve calculated (Figure 8), the hot zone temperature and the cold zone temperature (Figure 9).

The transition to the one zone model happens at 4.5min, time at which criteria C4 is encountered. The flashover happens at 5.6min. At this time, the rate of heat release switches to its steady state value of 12.5MW. The oxygen inside the compartment is then quickly consumed. Thus a ventilation regime occurs, leading to a rate of heat release of 8.6MW. The fire duration is increased. The areas below the two curves of Figure 8 are equal, all the energy available is released inside the compartment.

Step 4 Calculate the steel temperature
The steel temperature is evaluated for the unprotected and protected section. (Figure 10)
In this case, the design temperature time curve is the equivalent local temperature just above the fire source (Figure 9), obtained with the Hasemi's model, until the switch to the one
zone model at 4.5min. From 4.5 min to the end of the calculation, it is the one zone model temperature.

**Step 5: Calculate the member resistance**

The fire resistance of the unprotected steel section IPE400 is 10.2min.

With a protection thickness of 20mm of spray vermiculite, the critical steel temperature (507°C) of the member is higher than the steel temperature (471°C). In other words, the member resists during the whole fire duration, no failure of the member will occur.

![Figure 8 Input and calculated rate of heat release](image)

![Figure 9 Calculated compartment temperatures](image)
9 Conclusions

A computer tool has been developed to design steel elements submitted to compartment fires. This tool calculates successively:
- The design fire source (rate of heat release and mass loss rate);
- The gas temperature in the compartment;
- The temperature of a steel element in that fire compartment;
- The structural fire resistance of this element.

The definition of the design fire source is made according to a semi probabilistic method developed recently in a European research. This method enables to take into account active fire fighting measures.

The gas temperature calculation is made by a zone model. Different scenarios may occur depending on the results of the simulation. A two zone model is first applied, a switch to a one zone can occur if this model is more appropriate to the conditions inside the compartment. A modification of the rate of heat release may also occur if flashover conditions are encountered.

The temperature of steel section is calculated with the ENV1993-1-2 methods. The thermal solicitation is either the zone temperature or the equivalent localised temperature that includes the gas temperature and the direct radiant flux from a localised fire. The Hasemi’s method has been implemented to evaluate this local effect.

The structural fire resistance is evaluated according to ENV1993-1-2.

The code has a quite large field of application, it is suitable for pre and post flashover conditions, localised or fully engulfed fires. Nevertheless, it is limited to:
- A single compartment with quite simple shape suitable for zone modelling;
- A single fire source;
- In case of localised fire, fire resistance of beams at ceiling level.

Even if the code is primarily built to use the proposed design methodology, it remains open to other uses. Among other things, it enables to define new parameter values of the design fire curve, to modify the parameter values of the transition criteria or to build, point by point, other fire source (for example to simulate fire tests or more sophisticated design fires). It is also possible to use a two zone or a one zone model for the entire duration of a fire.

A Graphic User Interface has been developed to define the input data and view the results. The code is a freeware and is available at the University of Liege for general public.
The authors want to advise users that even if the code is "user friendly" and is able to give results in a short time, fires are very complex phenomenon. It is thus essential that any user must have a good knowledge of the dynamic of fires and that any result is fully analysed and fully understood. Among other thing, a single simulation is not sufficient in a decision process, sensitivity studies have to be conducted [17]. Moreover the figures provided for the input data (e.g. thermal properties, fire loads, rate of heat release,…) by the graphic interface are indicative values. They can be modified by the user who has full responsibility for the choice of these input data.

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References