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A new model for transient heat transfer model on external steel elements

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Abstract. The Eurocode system provides limited information regarding the structural fire design of external steel structures. Eurocode 1 provides thermal action for external member but only in steady-state conditions. On the other hand, Eurocode 3 provides a methodology to determine heat transfer to external steelwork, but there is no distinction in cross section shapes and, in addition, the calculated temperature distribution is assumed to be uniform in the cross section. This paper presents the results of a research carried out to develop a new transient heat transfer model for external steel elements to improve the current approach of the Eurocodes. This research was carried out as part of the project EXFIRE "Development of design rules for the fire behaviour of external steel structures", funded by the European Research Programme of the Research Fund for Coal and Steel (RFCS).

Keywords : fire safety design; external steel estructures,Eurocodes; thermal actions, thermal response, elevated temperatures; temperature distribution.

1. Introduction

Some architectural designs for outstanding buildings have become a challenge for the fire safety design; for example, nowadays it is becoming more common to show how some structural elements or the whole frame are designed and constructed, which has led to the structure to be built outside the building envelope. This is the case, for instance, in the George Pompidou Centre in Paris, France, or the Arts Hotel in Barcelona, Spain, among many others. A fire originated inside this kind of buildings can affect in a very different way the external elements from those which are within the fire enclosure.

Design for fire exposure to external steelwork is not new and Eurocodes provide some design guidance. Eurocode 1: "Actions on structures" - Part 1-2: "General actions - Actions on structures exposed to fire" provides in Annex B a simplified calculation method to determine thermal actions for external members.

To quantify external fire behaviour, Eurocode requires the following information: floor area of the fire compartment and the design fire load density related to the floor area, and the geometrical information about total area of vertical openings on the façade walls. From these data, Eurocode 1 gives:

- the maximum temperatures of the compartment fire,

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- the size and temperatures of the flame from openings,
- and the radiation and convection parameters.

But it is very important to underline that the Eurocode 1 Method considers only steady-state heat transfer for the all the parameters.

Regarding the "thermal response" of external steel structures, Eurocode 3: "Design of steel structures" Part 1.2 : "General rules Structural fire design", EN1993-1-2:2005, gathers a stationary model. This methodology is presented in the Annex B "Heat Transfer to external steelwork".

The limitations of this method are:

- the calculated temperature is an uniform steel temperature, taken for the most heated cross section of the external member,
- the approach is the same for all type of cross sections, there is no consideration of the real shape to take into account in a detail way the shadow effect.

This paper provides the result of a research intended to improve the current Eurocodes methodology.

2. Objetives of the model and presentation of the development methodology

To improve the Eurocodes approach to fire safety design of external steel structures, LABEIN-Tecnalia carried out the needed research and development works, to obtain a new transient heat transfer model, within the RFCS project EXTFIRE, "Development of design rules for the fire behaviour of external steel structures", (Joyeux et al. 2007).

The main aspects to be improved in the Eurocode's model are the following:

- Against the stationary model available currently, the new methodology deals with the transient effects related to a changing exposure to heat from flames and openings during the whole development of the fire.
- The Eurocode's, EN1993-1-2:2005, model treats open and hollow sections in the same way, with a section factor based method. The new approach uses an improved definition of configuration factors to take into account the shadow effect. Shadow zones are established in a profile's section and the net heat flux that reaches different points in the section is computed, considering the radiation flux from other parts of the section at different temperatures.
- In open cross sections, due to the different exposure to heat from flames and openings, a thermal gradient is created through the section. Therefore, all the parts do not undergo the same temperature evolution and need to be dealt with separately. The temperatures of web and flanges are calculated for each step of time.

To improve the Eurocode's, EN1991-1-2:2002, model it is proposed to develop a new model: a "transient heat transfer model", the EXTFIRE model. The main objectives for the new transient heat transfer model are summarised in the Table 1.

The methodology for the development of the EXTFIRE model has been based on the following philosophy:

Table 1 Summary of main objectives to be achieved by the new transient heat transfer model

Eurocode 1&3	EXTFIRE
Limitations	Objectives
Stationary model Steady-state conditions	Transient effect f(t)
Same approach for all type of the cross sections	Real shape of the sections
Uniform temperature in thecross section	Non uniform temperature in the cross section

- The EXTFIRE model must be based on amendment to the Eurocode method by using complementary and non contradictory information in other to make easier the upgrading of the Eurocodes with the EXTFIRE model.
- The validation of the model will be obtained by performing CFD, Computer Fluid Dynamics, simulations, see Fig. 1, and tests, see Fig. 2. This methodology has been assessed for the predictions of compartment fires providing realistic results (Lopes 2005).

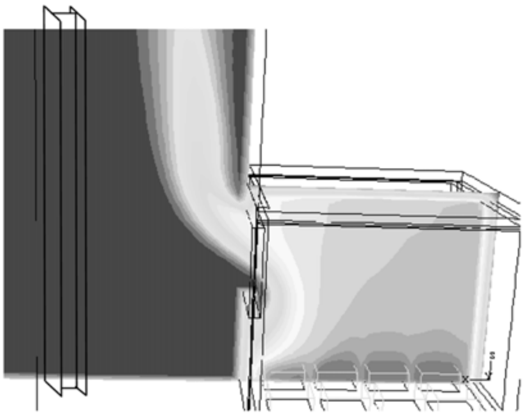

Fig. 1 Simulation of an external fire by CFD model

Fig. 2 Experimental external flaming – Efectis France

Tests performed by CTICM (France) and TNO (The Netherlands) were used for the validation of the new models during the duration of the RFCS project EXTFIRE.

The EXTFIRE methodology provides a performance based approach for fire safety design in which structural fire resistance of the external members could be evaluated in function of time, helping the designer to calculate a more realistic time to collapse.

3. Description of the EXTFIRE model

3.1 Assumptions for the EXTFIRE model

From the general assumptions for structural design and structural fire safety design in Eurocodes, for the EXTFIRE model, the following specific ones apply:

- The fire compartment is assumed to be confined to one storey only. All windows are assumed to be rectangular and with the same height.
- The temperature in the fire compartment and the parameters of the flames projecting from the openings (dimensions and temperatures) should be calculated separately.
- According to EN1993-1-2:2005, a distinction is made between members not engulfed and engulfed in flame, depending on the size of the external flames and the position of the elements. A member that is not engulfed in flame is assumed to receive radiative heat transfer from all the openings and flames. An engulfed member is assumed to receive radiative and convective heat transfer from the engulfing flame and radiative transfer from the opening from which it projects.
- Flames and openings are considered like radiating surfaces with a fixed temperature. An emissivity of 1 is considered for openings and for the flames, the specific emissivity depends on the thickness for the flames.
- No forced draught condition is assumed.

3.2 Thermal actions for external members

The simplified calculation method provide in Annex B: “Thermal actions for external members – Simplified calculation method” of Eurocode 1: “Actions on structures” - Part 1-2: “General actions - Actions on structures exposed to fire”, EN1991-1-2:2002, considers steady-state conditions for the determination of the parameters relevant to define the thermal actions for external members.

The simplified calculation method of Eurocode 1 provides the following characteristics of the fire in the compartment for no forced draught conditions: rate of burning or the rate of heat release, Eq. (1), temperature of the fire compartment, Eq. (2), and the flame dimensions, Eq. (3).

$$Q = \min\left((A_f \cdot q_{f,d}) / \tau_F ; 3,15 \cdot \left(1 - e^{\frac{-0.036}{o}}\right) \cdot A_V \cdot \left(\frac{h_{eq}}{D/W}\right)^{\frac{1}{2}} \right) \tag{1}$$

$$T_f = 6000 \cdot (1 - e^{-0.1/O}) \cdot O^{1/2} \cdot (1 - e^{-0.00286\Omega}) + T_0 \tag{2}$$

$$L_L = \max\left(0{:}h_{eq}\cdot\left(2.37\left(\frac{Q}{A_V\cdot\rho_g\cdot(h_{eq}\cdot g)^{\frac{1}{2}}}\right)^{\frac{2}{3}}-1\right)\right) \tag{3}$$

In addition to Eq. (3), Eurocode 1 provides additional figures, Fig. 3, and equations to define the flame dimensions in a comprehensive way, Table 2.

The improvement to this simplified approach of EN1991-1-2:2002 proposed by the EXTFIRE model is the consideration of transient effects of the fire. This is possible by using a rate of heat release depending on time according a realistic evolution of the fire in the compartment, instead of Eq. 1, which considers steady-state conditions, “no-time-dependant” fire.

The approach used by the EXTFIRE model is based on the utilization of a zone model with a prescribed rate of heat release depending on the fire load, see Fig. 4.

The growing phase is modelled as a t^2 function, depending on the type of building, and it is supposed that the decay phase is reached when the 70% of the fire load is consumed.

The temperature of the upper layer is considered in the compartment before flashover conditions were reached. After that, the RHR reaches suddenly the plateau, bringing forward the decay phase.

The approach based on the zone model, see Fig. 5, provides a realistic approach to analyze ventilation controlled fires, modifying the RHR taking into account the amount of oxygen available in the compartment.

The necessary input data to carry out the analysis of the fire conditions in the compartment are the

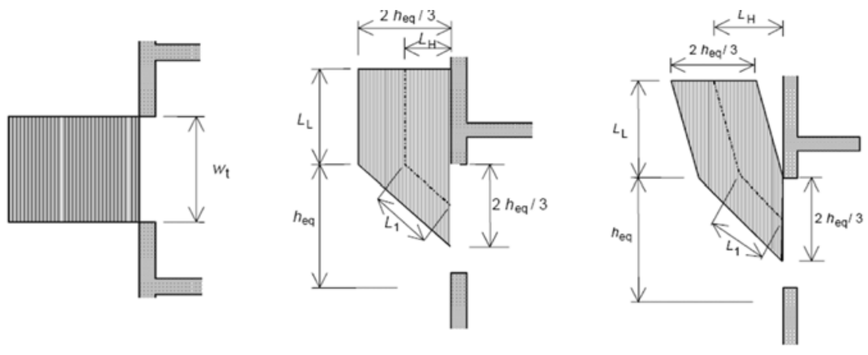

Fig. 3 Dimensions: Horizontal, left, and vertical cross sections, middle and right, of the flame and compartment opening in the facade. Source Eurocode 1.

Table 2 Flame dimensions for no forced draught conditions. Source Eurocode 1.

$h_{eq} < 1{,}25.w_t$	wall above	no wall above or $h_{eq} > 1{,}25.w_t$
$L_L = \dfrac{h_{eq}}{3}$	$L_1 = \sqrt{L_H^2 + \dfrac{h_{eq}^2}{9}} \cong \dfrac{h_{eq}}{2}$	$L_L \cong \dfrac{h_{eq}}{2}$
	$L_f = L_L + L_1$	$L_f = \sqrt{L_L^2 + \left(L_H - \dfrac{h_{eq}}{3}\right)^2} + L_1$

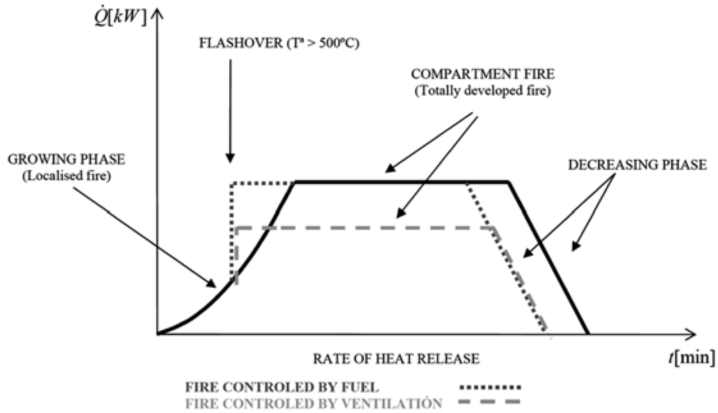

Fig. 4 Consideration of the transient effects of the fire. Rate of heat release for all the fire duration stages

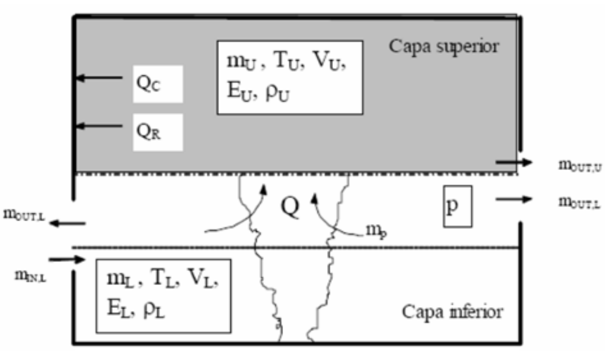

Fig. 5 Zone model of a compartment fire

following:

- Fire load, type, density and distribution.
- Combustion behaviour of the fire load.
- Compartment size and geometry.
- Ventilation conditions of the compartment.
- Thermal properties of the compartment boundaries.

Knowing fire temperature evolution in the compartment, flame properties are calculated according to Eqs. (2) and (3).

3.3 Open cross section columns not engulfed in flames

In open cross sections, due to transient effects related to different exposition to heat from flames and openings, a thermal gradient is created through the section. Therefore, all the parts do not undergo the same temperature evolution and need to be dealt with separately (web and flanges), (Wald 2006). Other effects are also accounted for in this kind of sections, such as shadow effect and radiating from other parts of the section at different temperatures. The temperature of each part is calculated for each step of time.

In concrete filled hollow steel sections, heat flux boundary conditions are calculated to use them in other FEM programs to obtain temperature distributions in the section.

Some references, (Renaud 2003), provide specific methodologies to take into account the effect of the interface slip between steel and concrete in composite columns, in order to obtain realistic results.

For open sections, the approach presented in this paper, the section is divided in three zones, the two flanges and the web. Each part of the section is going to receive different heat fluxes from openings and flames, so three different temperatures should be considered. Openings and flames are considered like radiating surfaces with a specific temperature and emissivity.

- The emmisivity of the radiating screen is 1 for windows, but for flames is calculated according to EN1993-1-2:2005:

$$\varepsilon = 1 - e^{-0.3 \cdot \lambda} \tag{4}$$

where λ is the flame thickness at the top of the window ($2h / 3$).

- The temperature of the radiating screen is the compartment temperature for windows. For flames, the temperature at a distance $h / 2$ from the opening measured along the flame axis should be used (calculated according to EN1991-1-2:2002).

The contributions of all flames and openings are summed to compute the whole radiative heat flux that arrives at each part of the element, considering that the absorptivity of flames is taken as 0 for not engulfed members. The convective heat transfer is neglected for not engulfed elements.

Shadow effect is studied for each radiating screen, in all the surfaces of the section. First the zone in shadow is calculated for each surface. Then, a uniform heat flux is considered in the radiated zone, whose value is calculated like the heat flux that arrives at the central point of this radiated zone (calculated according to EN1991-1-2:2002), considering the dimensions of the effective radiating surface for this point. Finally, the total heat flux that comes into contact with the radiated surface is assumed to be applied in the whole surface (flange or web, see Figs. 6 and 7).

$$\phi_{\perp}(x, y, z) = \frac{1}{2\pi}\left[\tan^{-1\left(\frac{y}{x}\right)}\left(-\frac{1}{\sqrt{1+\left(\frac{z}{x}\right)^2}}\right)\tan^{-1}\left(\frac{\frac{y}{x}}{\sqrt{1+\left(\frac{z}{x}\right)^2}}\right)\right] \tag{5}$$

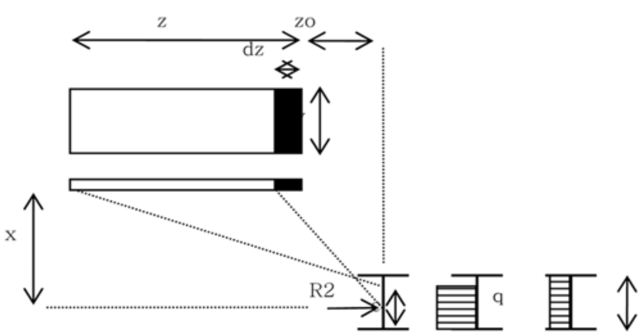

Fig. 6 Calculation of the configuration factor for the web

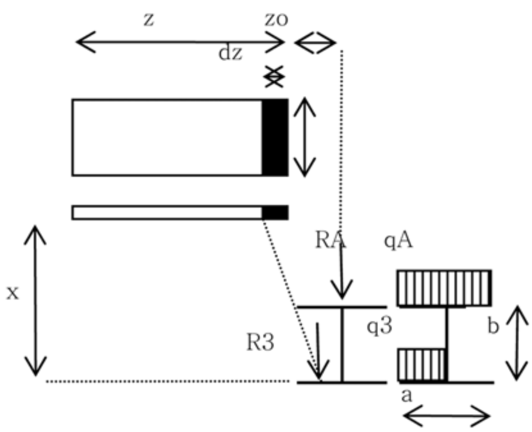

Fig. 7 Calculation of the configuration factor for the flanges

$$\phi_2 = \phi_\perp(x, y, zo + z) - \phi_\perp(x, y, zo + dz) \tag{6}$$

$$R_2 = \phi_2 \cdot \varepsilon \cdot \sigma \cdot T^4 \cdot (1 - a_z) \tag{7}$$

$$q_2 = R_2 \cdot c / b \tag{8}$$

$$\phi_{//}(x, y, z) = \frac{1}{2\pi}\left[\frac{\frac{y}{x}}{\sqrt{1+\left(\frac{y}{x}\right)^2}}\tan^{-1}\left(\frac{\frac{z}{x}}{\sqrt{1+\left(\frac{z}{x}\right)^2}}\right) + \frac{\frac{z}{x}}{\sqrt{1+\left(\frac{z}{x}\right)^2}}\tan^{-1}\left(\frac{\frac{y}{x}}{\sqrt{1+\left(\frac{z}{x}\right)^2}}\right)\right] \tag{9}$$

$$\phi_A = \phi_{//}(x - b, y, zo + z) - \phi_{//}(x - b, y, zo) \tag{10}$$

$$\phi_3 = \phi_{//}(x, y, zo + z) - \phi_{//}(x, y, zo + dz) \tag{11}$$

$$R_A = \phi_A \cdot \varepsilon \cdot \sigma \cdot T^4 \cdot (1 - a_z) \tag{12}$$

$$R_3 = \phi_3 \cdot \varepsilon \cdot \sigma \cdot T^4 \cdot (1 - a_z) \tag{13}$$

$$q_A = R_A \tag{14}$$

$$q_3 = R_3 \tag{15}$$

The interaction between surfaces is considered to compute the net radiative heat flux that each surface absorbs. The surfaces of the member are considered like gray surfaces ($\varepsilon = \alpha = 1 - \rho$). It is assumed that fictitious surfaces absorb all the radiation they receive (See Fig. 8).

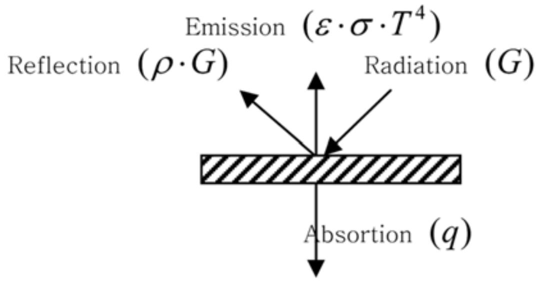

Fig. 8 Interaction between surfaces

$$J = \varepsilon \cdot \sigma \cdot T^4 + \rho \cdot G \rightarrow Radiossivity \tag{16}$$

$$q = G - J \tag{17}$$

The radiossivity of each part is the sum of the emission due to temperature, the reflection of the radiation from the environment and the reflection of the radiation from the other parts of the section.

$$J_i = \varepsilon \cdot \sigma \cdot T^4 + \sigma \cdot T_o^4 \cdot \rho + q_i \cdot \rho + J_j \cdot F_{j,i} \cdot \rho + J_k \cdot F_{k,j} \cdot \rho \tag{18}$$

The temperature of each part of the section used to compute the term of emission is delayed a step with the others ones, because this is just the wanted parameter.

The whole phenomenon of reflections, emissions… between all the parts of the section can be studied solving a linear equations system which collects all the heat balances.

$$\vec{J} = [A]^{-1} - \vec{v} \tag{19}$$

After that it is possible to solve the heat balance to calculate the temperature in the different zones of the section (See Fig. 9).

$$Q_i = q_i + \sigma \cdot T_0^4 - J_i + F_{j,i} \cdot J_j + F_{k,i} \cdot J_k \tag{20}$$

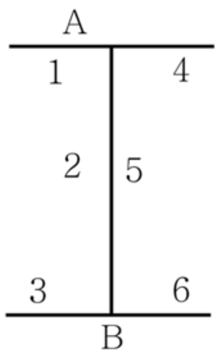

Fig. 9 Surfaces in the section

The increase of temperature in each step of time is computed according to EN1993-1-2:2005.

$$h_{flange1} = \frac{a}{2} \cdot Q_1 + \frac{a}{2} \cdot Q_4 + a \cdot Q_4 \tag{21}$$

$$h_{web} = b \cdot Q_2 + b \cdot Q_5 \tag{22}$$

$$h_{flange2} = \frac{a}{2} \cdot Q_3 + \frac{a}{2} \cdot Q_6 + a \cdot Q_B \tag{23}$$

$$\Delta\theta = \frac{h_s \cdot \Delta t}{\rho \cdot C_p \cdot l \cdot e} \tag{24}$$

When the column is between two openings, two radiating surfaces are considered in each side of the element. These surfaces have a specific temperature and emissivity.

- The emmisivity of the radiating screen is calculated for each side according to EN1993-1-2:2005:

$$\varepsilon_m = 1 - e^{-0.3 \cdot \lambda m} \tag{25}$$

$$\lambda_m = \sum_{i=1}^{m} w_i \tag{26}$$

$$\varepsilon_n = 1 - e^{-0.3 \cdot \lambda n} \tag{27}$$

$$\lambda_n = \sum_{i=1}^{n} w_i \tag{28}$$

where w_i is the width of each opening, m is the number of openings on side m and n is the number of openings on side n.

- The temperature of the radiating screen is the temperature at a distance $h/2$ from the opening measured along the flame axis should be taken (calculated according to EN1993-1-2:2005).
- The contributions of the two flames are summed to compute the whole radiative heat flux that arrives at each part of the element. The radiative heat transfer from the windows and the convective heat transfer are neglected.

Shadow effect is studied for each radiating screen in a similar way as the method presented in part 3.1. In this case there are not zones in shadow, but the effective screen dimensions for each zone must be calculated.

The interaction between surfaces and the calculation of heat fluxes and temperatures are calculated similarly as before.

3.4 Open cross section columns engulfed in flames

An engulfed member is assumed to receive radiative and convective heat transfer from the engulfing flame and radiative transfer from the opening from which it projects. Four fictitious radiating surfaces are considered enclosing the section in order to model the engulfing flame. The opening is considered like a radiating surface with a specific temperature and emissivity.

- The emmisivity of the radiating screen is 1 for windows, but that for flames is calculated according to EN1993-1-2:2005 (See Fig. 10):

$$\varepsilon = 1 - e^{-0.3 \cdot \lambda} \tag{29}$$

where λ is the flame thickness at the top of the window ($2h/3$).

- The temperature of the radiating screen is the compartment temperature for windows. For flames, the temperature at a distance $h/2$ from the opening measured along the flame axis should be taken (calculated according to EN1993-1-2:2005).

The absorptivity of flames and the convective heat transfer are calculated according to Eurocode:

$$a_z = \frac{\varepsilon_A + \varepsilon_B + \varepsilon_C}{3} \tag{30}$$

$$a = 4.67 \cdot \left(\frac{1}{d_{eq}}\right)^4 \cdot \left(\frac{Q}{A_v}\right)^{0.6} \tag{31}$$

$$d_{eq} = \frac{a+b}{2} \tag{32}$$

where A_v is total area of vertical openings on all walls.

Shadow effect is only studied for the window radiating screen in a similar way to the method presented before.

The interaction between surfaces is considered to compute the net radiative heat flux that each surface

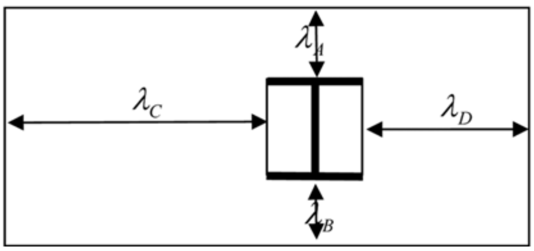

Fig. 10 Surfaces in the section

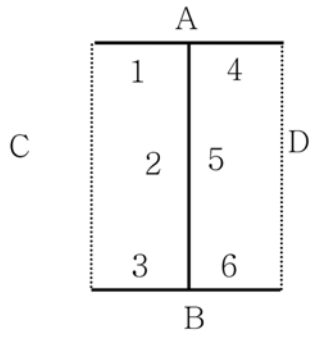

Fig. 11 Surfaces in the section

absorbs. The surfaces of the member are considered like gray surfaces ($\varepsilon = \alpha = 1 - \rho$) (See Fig. 11).

The radiossivity of each part is the sum of the emission due to the temperature, the reflection of the radiation from the environment and the reflection of the radiation from the other parts of the section.

$$J_i = \varepsilon \cdot \sigma \cdot T^4 + \sigma \cdot T_o^4 \cdot \rho + q_i \cdot \rho + J_j \cdot F_{j,i} \cdot \rho + J_k \cdot F_{k,i} \cdot \rho + J_C \cdot F_{C,i} \cdot \rho \tag{33}$$

The temperature of each part of the section used to compute the term of emission is delayed a step with the others ones, because this is just the wanted parameter.

The whole phenomenon of reflections, emissions… between all the parts of the section can be studied solving a linear equations system which collects all the heat balances.

$$\vec{J} = [A]^{-1} \cdot \vec{v} \tag{34}$$

After that it is possible to solve the heat balance to calculate the temperature in the different zones of the section.

The increase in temperature in each step of time is computed according to EN1993-1-2:2005.

$$h_{flange1} = \frac{a}{2} \cdot Q_1 + \frac{a}{2} \cdot Q_4 + a \cdot Q_A + 2 \cdot a \cdot a \cdot (T_{flame} - T_{flange1}) \tag{35}$$

$$h_{web} = b \cdot Q_2 + b \cdot Q_5 + 2 \cdot b \cdot \alpha \cdot (T_{flame} - T_{web}) \tag{36}$$

$$h_{flange2} = \frac{a}{2} \cdot Q_3 + \frac{a}{2} \cdot Q_6 + a \cdot Q_B + 2 \cdot a \cdot \alpha \cdot (T_{flame} - T_{flange2}) \tag{37}$$

$$\Delta\theta = \frac{h_s \cdot \Delta t}{\rho \cdot C_p \cdot l \cdot e} \tag{38}$$

3.5 Close cross section columns

Due to the shape of the section, neither shadow effect nor interactions between surfaces are taken into account.

Heat flux boundary conditions are calculated to use them in other FEM programs to obtain the temperature distribution in the cross-section.

4. Validation

A fire compartment was built at the TNO Centre for Fire Safety for the purpose of carrying out full-scale experiments of external flaming acting on unloaded steel structures. Several tests were carried out for various compartment and opening dimensions, to study the effect of each parameter on the thermal action and thermal response of steel structures.

The size of the furnace is 4.4 m of length, 4 m of width and 2.6 m of height. The fire compartment is constructed from cellular concrete blocks of thickness 150 mm.

Two openings are placed symmetrically as shown in Fig. 12. A promatec panel of height 3 *m* was attached to the top of the compartment in order to represent the façade of the upper floor of a typical multi-stored building.

Three columns are placed in front of the compartment as shown in Fig. 12, a HEA 200 and two rectangular concrete filled SHS columns (300 mm × 300 mm) (See Fig. 12).

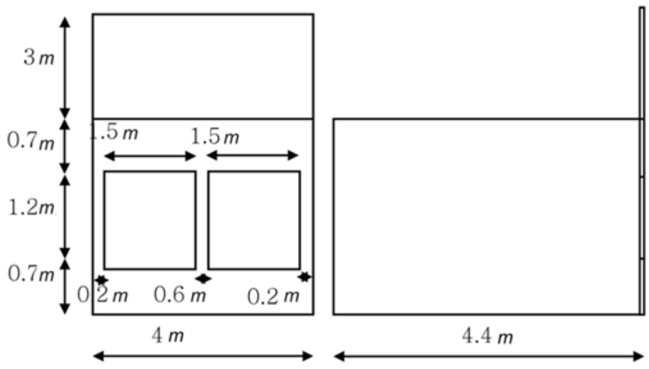

Fig. 12 Experimental set up

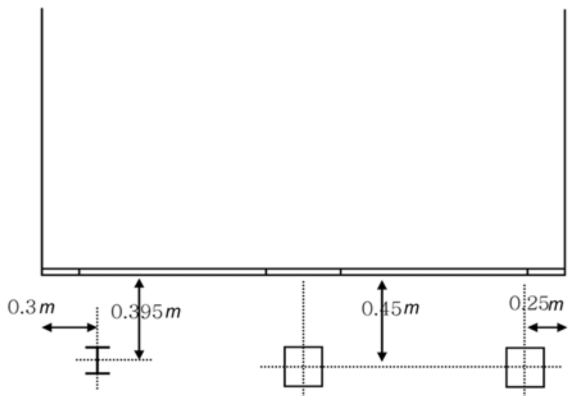

Fig. 13 Columns in front of the fire compartmente

The fire source is made up of 42 wooden Europallets stacked on a platform hanging about 0.1 m above the floor of the compartment (1,050 Kg of wood). The fire load density is 60 Kg/m^2.

Test data are used to simulate the compartment and flame properties:

- The highest measured values are taken for the opening and flames temperatures, and the mean value for the room temperature.
- The convection coefficient is calculated according to the Law model, so the heat release rate is not necessary for columns.
- External flaming occurs from 660 to 3000 sec, as shown in the test.
- The other flame properties not described in the research results (Joyeux *et al*. 2007) are calculated according to the Law model.

The steel temperature was measured at 2.1 m above floor level. The measuring section was equipped by thermocouples distributed as shown in the Fig. 14.

5. Conclusions

There is a very good agreement between test and model results, discrepancies are due to how the thermal action is defined.

The current model of the Eurocode could give results on the unsafe side, because peak temperatures are higher than the steady-state temperature predicted with the current model.

For open sections, the results given by the model are quite close to tests results, lying in the safe side. Discrepancies are not quite large to render the model too conservative.

For composite sections, due to the low conductivity of concrete, large gradients occur, and a finite element simulation was conducted after calculation of heat fluxes on the steel perimeter. A simplified 1D model has been checked, and in some cases it is a good estimate of heat transfer within the section. If the peak temperature is the target of the calculation, this approach trends to overestimate the temperature of the hottest point of the section because it neglects conduction to colder parts of the steel perimeter.

Otherwise, if a full description of temperature rise is targeted, it trends to underestimate temperature rise of the coldest points. This results in an overestimation of thermal gradient within the section due to accidental actions. If the bending moment induced by this thermal gradient sums up to the initial bending moment this result is not unsafe, otherwise, in the beginning of fire exposure it leads to a reduction of the actual bending moment acting on the member. This effect may be neglected once high temperatures within the section take the role in structural response and accidental induced actions do

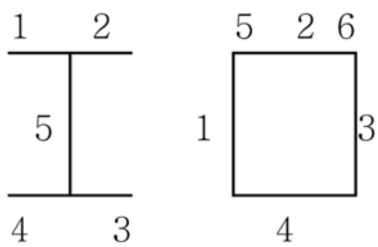

Fig. 14 Thermocouples distribution

Fig. 15 Experimental external flaming - Efectis Nederland

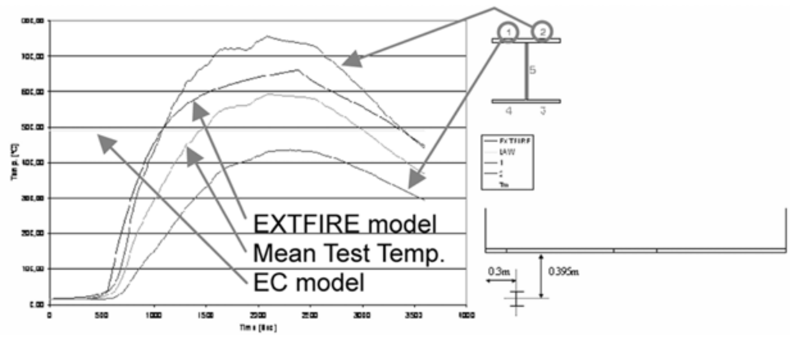

Fig. 16 Experimental validation of results

not play the main role in collapse mechanism.

The model has been implemented in a software (EXTFIRE) developed by LABEIN TECNALIA to make easier its application, and it has been validated with several fire tests carried out by CTICM and TNO during the development of the RFCS project mentioned before, being in a good agreement with test results.

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