European Commission

technical steel research

Steel products and applications for building, construction and industry

Development of design rules for the fire behaviour of external steel structures

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1 OBJECTIVES OF THE PROJECT

The objectives of the present research are recalled below. This work in intended:

- To improve the existing model for determining the thermal actions on external bare, insulated or shielded structural elements, taking into account radiative and convective heating by external flames and by the opening of the compartment in fire itself

- To extend the existing physical model for temperature development within structural elements (steel or composite) by including transient state conditions and, when necessary, the effects of fire protection systems such as fire insulation and thermal shielding, taking into account heat transfer across air gaps

- To verify the developed models on the basis of experimental results and to adapt the models, where appropriate

- To develop simple rules on the heating of bare or protected external steel sections, steel section away from a localized fire and balconies, in case of fire

The effort has been divided in 6 work packages. A single work package is about the coordination of the activities. The first work package is devoted to the estimation of thermal actions to structural elements. The others deal with the temperature response of specific types of structural elements or specific fire protection conditions. Within each work package, three types of work are considered. These types are:

- adjustment and development of models, on the basis of literature and numerical tools results
- experimental verification of models predictions
- development of simple rules to estimate the heating of external members during a fire

The title and the tasks associated with each work package are summarized in the table below.

Work package	Tasks
WP 1 Projection of external flames by openings Co-ordination: TNO	1. Experimental testing in flame projection 2. Numerical simulations 3. Development of simple calculation method for thermal actions
WP 2 Heating up of steel or composite bare sections Co-ordination: Labein	1. Numerical simulations 2. Development of simple calculation method for heating of bare steel and composite sections
WP 3 Heating up of protected steel sections Co-ordination: CTICM	1. Experimental testing of heating of bare and protected steel sections 2. Numerical simulations 3. Development of simple calculation method
WP 4 Heating up of external steel sections protected with steel box and of balconies Co-ordination: VTT	1. Experimental testing of protected steel sections and balconies 2. Numerical simulations 3. Development of simple calculation method on sections protected by steel box and balconies
WP 5 Heating up of sections by localised fires Co-ordinator: ProfilARBED	1. Experimental data of heating of steel sections from localised fire 2. Numerical simulations 3. Development of simple calculation method
WP 6 Coordination Co-ordination of the project : CTICM	

Table 1 - Work packages and corresponding tasks

The work undertaken has followed the technical annex accepted for the present research project. The technical annex is given in the annex 2 of the present report. The present research started in 2002 and ended in December 2005.

2 COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACCOMPLISHED

2.1 Management of the project

Responsible partner: CTICM
Objectives: Overall management of the project.

The project has been coordinated by CTICM. This coordination has consisted in holding meetings during the research, and ensuring that the work schedule was respected as far as possible[1]. For every meeting, minutes have been written in order to give a summary of actions to be performed by each partner. The coordinator was also in charge of the semestrial, annual and final reports, and presentations to the TGS8 committee.

During this research, communication has been established with Margaret Law. She has given her opinion about the weakness of her model and about recent literature on external flames.

The meetings held since the beginning of the research are summarized in the table below.

N°	DATE	PLACE	ATTENDANT	ACTIONS
1	20 September 2002	**Paris** (Fr)	**ProfilARBED Research** Olivier VASSARD Louis Guy CAJOT **CTICM** Daniel JOYEUX Joel KRUPPA **VTT** Jukka MYLLYMAK **TNO** Tony LEMAIRE Leen TWILT **LABEIN** Jesus De La QUINTANA Javier UNANUA	-Presentation of the project -Literature review
2	16 January 2003	**Paris** (Fr)	**ProfilARBED Research** Mike HALLER Louis Guy CAJOT **CTICM** Sylvain DESANGHERE Daniel JOYEUX Joel KRUPPA **VTT** Jukka MYLLYMAK **TNO** Tony LEMAIRE **LABEIN** Jesus De La QUINTANA Javier UNANUA	-Benchmark definition -Review on experimental data -Literature review
3	28 June 2003	**Bilbao** (Sp)	**ProfilARBED Research** Mike HALLER **CTICM** Sylvain DESANGHERE Daniel JOYEUX **VTT** Olli KAITILA **TNO** Tony LEMAIRE Leen TWILT **LABEIN** Jose Miguel FERNANDEZ Javier UNANUA	-Benchmark part 2 -Going on experimental data review -Study of several parameters

[1] An extension of 6 months has been requested due to delay about experimental works and was accepted by European Commission.

4	17 October 2003	**Delft** (Nl)	**ProfilARBED Research** Mike HALLER **CTICM** Sylvain DESANGHERE Daniel JOYEUX **VTT** Olli KAITILA **TNO** Tony LEMAIRE Leen TWILT **LABEIN** Javier UNANUA	-Benchmark part 3 -Going on experimental data review -Study of several parameters -Tests definition
5	12 February 2004	**Esch/Alzette** (Lu)	**ProfilARBED Research** Mike HALLER Louis Guy CAJOT **CTICM** Sylvain DESANGHERE Daniel JOYEUX **VTT** Olli KAITILA **TNO** Tony LEMAIRE Leen TWILT **LABEIN** Javier UNANUA	-Benchmark conclusion -Going on experimental data review -Study of several parameters - Tests definition
6	3-4 June 2004	**ESPOO** (Fin)	**ProfilARBED Research** Mike HALLER **CTICM** Sylvain DESANGHERE Daniel JOYEUX **VTT** Olli KAITILA **TNO** Tony LEMAIRE Leen TWILT **LABEIN** Javier UNANUA	- Benchmark conclusion -Going on experimental data review -Study of several parameters - Tests definition - Realisation of tests by VTT
7	14-15 October 2004	**Maizieres lès Metz** (Fr)	**ProfilARBED Research** Mike HALLER **CTICM** Sylvain DESANGHERE Daniel JOYEUX **VTT** Olli KAITILA **TNO** Tony LEMAIRE **LABEIN** Javier UNANUA	- Reorganisation of the work packages - Realisation of experimental test by CTICM - Study of several parameters
8	10-11 March 2005	**Delft** (Nl)	**ProfilARBED Research** Mike HALLER **CTICM** Sylvain DESANGHERE Daniel JOYEUX **VTT** Olli KAITILA **TNO** Tony LEMAIRE **LABEIN** Javier UNANUA	- Analysis of the tests performed by TNO and CTICM - Review of the proposals for the global transient methodology - Analysis of the method for thermal transfer to structures - Schedule of the research
9	13-14 October 2005	**Bilbao** (Sp)	**ProfilARBED Research** Mike HALLER **CTICM** Sylvain DESANGHERE Daniel JOYEUX **VTT** Olli KAITILA **TNO** Tony LEMAIRE **LABEIN** Javier UNANUA Fernando MORENTE	- State of the work - Example of application of the method - Final report

Table 2 - Project meetings

The work schedule of the project has been brought up to date and is given in the tables below.

	Months						
Task Groups	2002	2003		2004		2005	
	7-12	1-6	7-12	1-6	7-12	1-6	7-12
TG A - Co-ordination							
TG B - Projection of external flames by openings	Task 1	Task 1	Task 2	Task 2	Tasks 2 and 3	Task 3	Task 3
TG C – Experimental data							
TG D - Heating up of steel or composite bare sections							
TG E - Heating up of protected steel sections							
TG F - Heating up of external steel sections protected with steel box and of balconies							
TG G - Heating up of sections from localised fires							

Table 3 - Work schedule

2.2 Communication

During the research, communications were made about the project.

The project was the object of a PhD (S. Desanghere) at CTICM, from 1st January 2003 to 31st december 2005. The PhD will be presented by the end of the 1st semester of 2006.

The project was the object of master student work in VTT and in Arcelor Research Center.

An overview of the project was presented in a finish conference. Herebelow is given the reference of the paper:

Kaitila, O., ECSC-projekti "Ulkopuolisten teräsrakenteiden kestävyys tulipalossa" (ECSC-Project "Development of design rules for the fire behaviour of external steel structures"), Teräsrakenteiden tutkimus- ja kehityspäivät (Finnish Steel Structures R&D Days), Seinäjoki, Finland, 2-3.9.2004 (in Finnish)

3 DESCRIPTION OF ACTIVITIES AND DISCUSSION

3.1 Experimental work

Within the project, a review of many tests performed from 1970 to now has been done.

The analysis was mainly focussed on tests integrating added value for the present project:

- balconies tests from VTT used within the TG F about the improvement of the Eurocode 1 model concerning the effect of balconies on flame deviation (ref n°15, VTT)
- external flaming tests performed with protected steel elements (more recent tests performed at CTICM), (ref n°59 to n°67 – CTICM)
- external flaming tests performed with hollow core steel sections filled of concrete (recent tests performed, ref n°71- CTICM)
- External flaming with wall properties effect (ref n°5 and 6, CTICM tests)
- External flaming with lateral wind effect (German study)

Nevertheless, additional tests were necessary for validation of the global methodology. So, experimental work has been performed as presented in the technical annex. Several tests have been realized by VTT, CTICM and TNO.

The objectives of the tests were:

- validation of parameters effects of the eurocode model relevant to the WP1
- validation of the heating response model for composite structures (WP2)
- validation of the heating response model for protected steel sections by intumescent coating (WP3)
- validation of the heating response model for encased structures (WP4)

All the results are provided in a CDROM joined to the final reports, in terms of analysis of the results, reports and excel results. The results are also used for each WP work, presented as comparison in their appendix reports. The following chapters are just short presentations of the tests performed by the three partners.

It can be noticed that Arcelor gave freely the steel sections used during the different tests.

3.1.1 Tests performed by VTT

Four structural fire tests have been carried out in 2004 as part of the ECSC research project PR380 "Development of design rules for the fire behaviour of external steel structures". The test data is used in the development of numerical calculation methods for the evaluation of the fire resistance of external steel structures.

The fire tests were carried out using the VTT Building and Transport facade apparatus. The columns were placed in front of the 3000 mm × 1200 mm large fire room window in order to study the heating up of external steel columns with different types of fire protection. A total of 12 columns were tested - three columns in each of the four tests. In each test, two columns were placed symmetrically in front of the fire room window and one column was placed at the level of the side of the window.

The results can be used to provide basic data on the influence of a selection of different fire protection methods on the temperatures of the columns and to study the differences in the temperature development between structural steel columns and stainless steel columns.

The fire load consisted of wood cribs (made with 38 mm × 40 mm × 800 mm wood battens) and particle boards with total weights of approximately 375 kg and 260 kg, respectively, corresponding to an approximate fire load density of 180 MJ/m2 calculated for the total room area and 986 MJ/m2 calculated for the floor area, when the heat of combustion of wood is 14 MJ/kg. The fire load was designed so as to have flames coming out of the fire room window for about 30 minutes.

Six column types with different fire protection materials were tested as summarized in Table 4. These column types were also tested in fire resistance testing conditions according to standard ISO fire for comparison in the Horizontal Furnace. All columns were of 4500 mm length. The stainless steel grade was AISI 304 (EN 1.4301) and the structural steel grade for columns was S355 (EN 10025) and DX51 (EN 10142) for PVDF-coated casings.

Column type tag	Number of tested specimens	Column profile	Column material	F/V [1/m]	Fire protection
M-RHS-Paint	1	RHS 150x150x5	S355 Structural steel	206	Intumescent paint
S-RHS-Sbox	3	RHS 150x150x5	AISI 304 Stainless steel	206	Stainless steel casing
M-RHS-Sbox	3	RHS 150x150x5	S355 Structural steel	206	Stainless steel casing
S-RHS-Unp	1	RHS 150x150x5	AISI 304 Stainless steel	206	None
M-RHS-MBox	2	RHS 150x150x5	S355 Structural steel	206	PVDF-coated structural steel casing
M-HEA-Mbox	2	HEA 200	S355 Structural steel	212	PVDF-coated structural steel casing

Table 4 - Description of test specimen types

One structural steel RHS column was protected with intumescent paint UNITHERM 38091 External, one stainless steel RHS column was left bare and the remaining columns were protected with a thin steel sheet casing made of either stainless steel or structural steel with PVDF-coating. An air gap of approximately 12 mm was left between the column and the casing. The ends of the columns were closed using welded steel plates and stone wool insulation in order to prevent the flow of hot gases through the ends.

To get a general overview of the results, the maximum temperatures reached for each column specimen during the tests are collected in Table 5.

Test # - Column #	*Specimen type*	*Maximum temperature reached during the test*	*Time from ignition to reaching maximum temperature*	*Thermocouple number*	*Thermocouple location*
T1-C1	M-RHS-Sbox	989°C	26 min	1031	*h* = 3560 mm, toward window
T1-C2	S-RHS-Sbox	911°C	27 min	1076	*h* = 3560 mm, toward window
T1-C3	M-RHS-Mbox	548°C	33 min	1091	*h* = 1960 mm, toward window
T2-C1	S-RHS-Unp	971°C	14 min 30 s	2016	*h* = 2760 mm, toward window
T2-C2	M-RHS-Sbox	789°C	22 min	2061	*h* = 2760 mm, toward window
T2-C3	S-RHS-Sbox	484°C	35 min	2091	*h* = 1960 mm, toward window
T3-C1	S-RHS-Sbox	866°C	20 min	3016	*h* = 2760 mm, toward window
T3-C2	M-HEA-Mbox	808°C	31 min	3077	*h* = 3560 mm, toward window
T3-C3	M-RHS-Sbox	493°C	35 min 40 s	3091	*h* = 1960 mm, toward window
T4-C1	M-RHS-Mbox	821°C	34 min	4001	*h* = 1960 mm, toward window
T4-C2	M-RHS-Paint	479°C	32 min	4079	*h* = 3560 mm, right side
T4-C3	M-HEA-Mbox	549°C	35 min	4092	*h* = 1960 mm, toward window

Table 5 - Maximum temperatures reached for each specimen during the tests

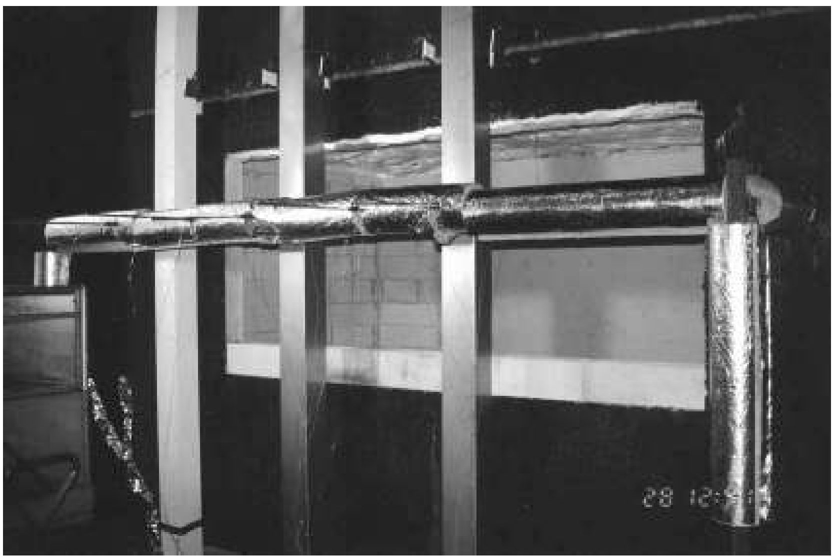


Figure 1 - Overview of VTT test 1

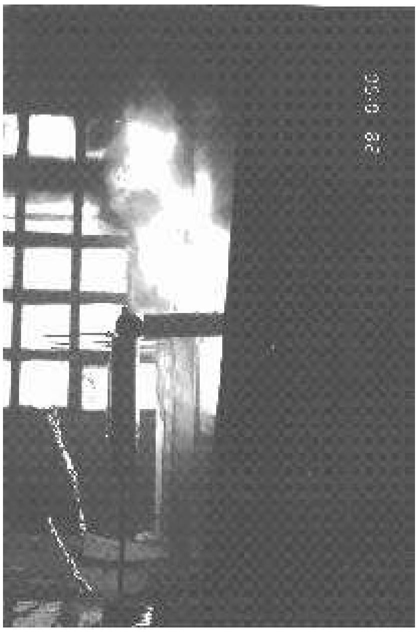
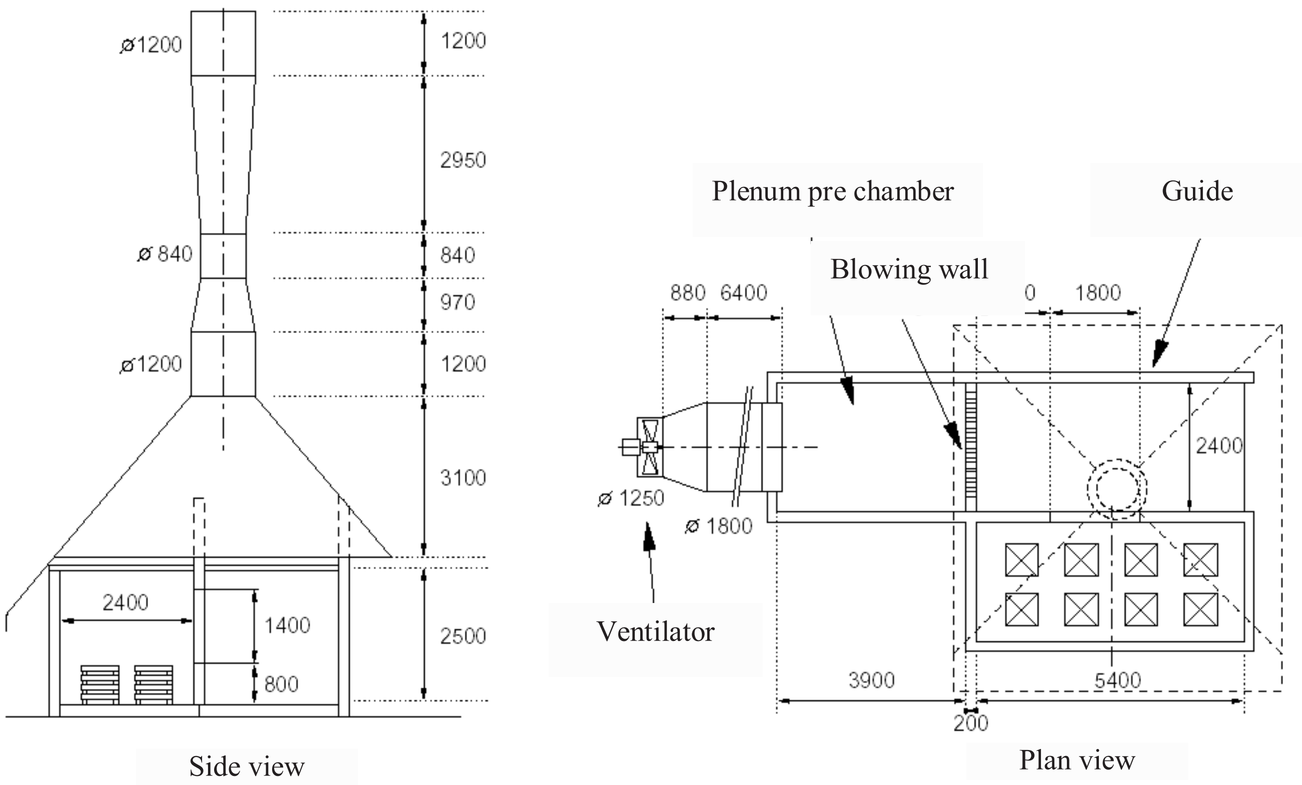


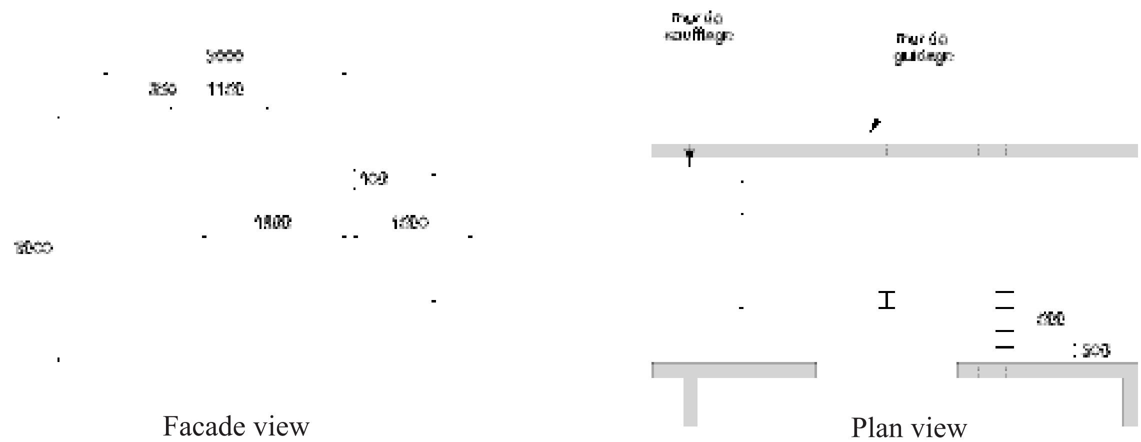
Figure 2 - Flames bursting out the window during Test 1

A small test series for the evaluation of the emissivity of stainless steel has started in May 2004. The results were used in the WP4 for assessing the radiating heat exchange between the structural element and the encasing element.

3.1.2 Tests performed by CTICM

A series of 6 experimental tests has been performed by CTICM within the framework of the research, in order to study the effect of wind on external flames and on the heating of external elements. These experiments have been carried out using a calorimeter hood described in Figure 3.





Facade view Plan view

Figure 3 - Overview of experimental tests (3 and 4) performed by CTICM

The fire load was made of wood cribs (leading to natural fire) and the same compartment was used for each test. This one was made of cellular concrete. A ventilator and a plenum pre chamber constitute a system of blowing used to simulate the effect of the wind.

The speed of the flow has been recorded using bidirectional probes [1, 2] at several locations. The furnace's dimensions are 5.40 m by 2.40 m, with an elevation of 2.50 m. A weigh platform is also used to record the mass loss of the fire load. In order to simulate the presence of a second floor above the compartment, the facade wall is higher than the ceiling.

Several fire loads and two kinds of opening have been employed. The main characteristics of the tests are given in Table 6.

Test	Fire load (kg)	Opening (w*h)	Wind speed (m/s)
1	940	1.80*1.40	0
2	450	1.80*1.40	0
3	600	1.80*1.40	0
4	620	1.80*1.40	2
5	620	1.40*1.40	6
6	620	1.40*1.40	10

Table 6 - Characteristics of the tests

The tests chronology is the following:

- Test 1: first test designed to check the experimental device, with only one element
- Test 2: second test, same as the first one but using a different fire load
- Test 3: reference test with all element placed and in blowing configuration but without wind
- Test 4: Blowing at 2 m/s but with bad quality of flow
- Test 5: Blowing at 6 m/s with a new blowing configuration
- Test 6: Blowing at 10 m/s with the same configuration

Figure 4 - CTICM Test 1: One column located in front of the opening - Facade view

3.1.3 Tests performed by TNO

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. Four tests were carried out for various compartment and opening dimensions (henceforth denoted Test 1 to Test 4).

Main objectives of the fire tests performed at TNO were:

- To study the effect of the compartment geometry on:
    - the thermal action (compartment temperature and flame properties) on the external steel structures
    - the thermal response of the external steel structures
- To study the effect of the window geometry on the thermal action and thermal response
- To compare the measured thermal actions with available theoretical models
- To provide experimental data for verification of numerical models of the thermal response of hollow core steel columns filled with concrete

In order to systematically study the effect of the compartment and window geometry only one parameter was changed per test, with the external structures fixed on the same position (in front of the facade with the windows) during all four tests. Unprotected steel profiles and composite (hollow core steel section filled of concrete) were used closed to the opening for measuring the temperature reached in the column.

The following parameter variation was carried out:

- Test 1: short compartment with one wide window of standard height
- Test 2: short compartment with two small windows of standard height
- Test 3: deep compartment with two small windows of standard height

* Test 4: deep compartment with two small windows of extended height

The depth of the deep compartment was twice the depth of the short compartment.

The width of the wide window was twice the width of a small window. The fire load of the deep compartment was twice the fire load of the short compartment.

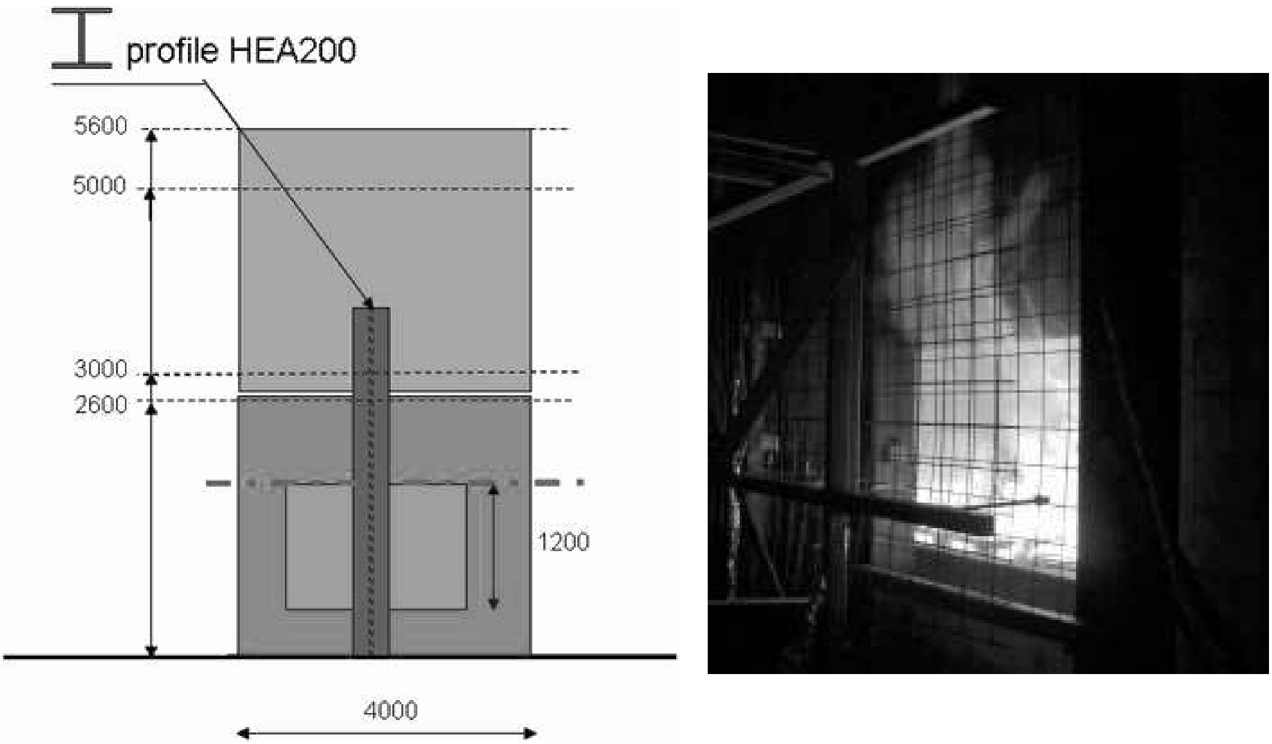


Figure 5 - TNO experimental setup

3.2 Development of a model intended to predict transient thermal actions to external structure

Responsible partner: TNO	**Other partners:** CTICM,LABEIN,VTT
Objectives: Development of methods to predict the heat flux to structural elements from external plumes.	

This work uses Computational Fluid Dynamics techniques (CFD) and experimental data to help developing a model for predicting thermal actions to external structure. The present model has to calculate geometry, temperature and composition of flames emerging from openings. Convective and radiative heat transfer to structural elements within or adjacent to these flames has also to be predicted.

A sensibility analysis has been carried out to ensure the reliability of eurocode models on the given ranges, and for the development of simple calculation rules for estimating thermal exposure and heat transfer to structural elements located outside a burning compartment.

The following synthesis is based on technical results provided in annex 1.

3.2.1 Validation of numerical tools

The first part of this work has been devoted to the validation of the CFD tools employed during the research. A validation case has been proposed, on the basis of an experimental test performed by CTICM by the end of the seventies. This test corresponds to a compartment natural fire with about hundred thermocouples placed outside the room in order to measure the temperature field during the course of the fire.

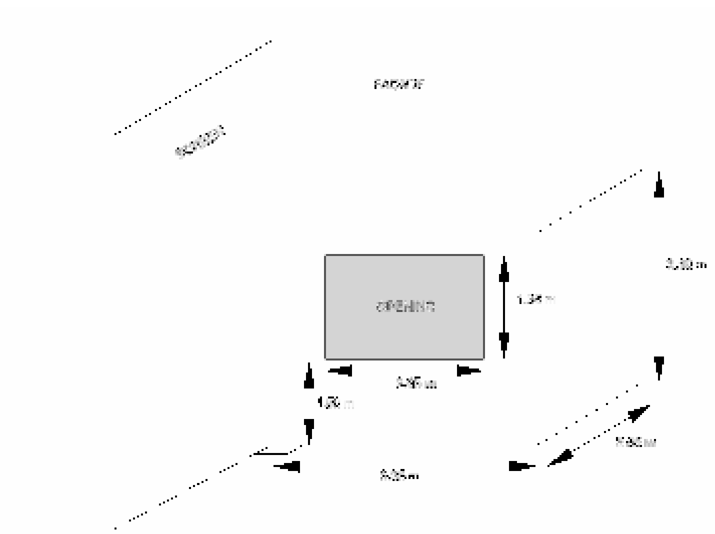


Figure 6 - Overview of the benchmark case

This configuration has been used as a benchmark case aimed at evaluating the CFD tools as well as the use of such tool by each partner. The CFD codes employed are:

- Fire Dynamics Simulator (CTICM and VTT)
- FLUENT (LABEIN)
- SOFIE (ARBED)
- VESTA (TNO)

The mass loss rate was measured during the test and is used as an input value for CFD simulations. The comparisons between calculations results and experimental data concern mainly temperatures at different locations.

Different simulations have been carried out and the final results lead to the following conclusions:

- CFD tools can predict the external temperature field with a relatively good agreement with experimental data
- Such tool can be used to study the influence of some key parameters on external flames
- It appears that FLUENT and FDS are the most appropriated tools for studying external flames
- This study has shown that CFD tools can be exploited with confidence at least to get qualitative results about external flaming

3.2.2 Study of main parameters affecting external flames characteristics

The study of several important parameters affecting external flames characteristics has been performed in order to check if the current models take them correctly into account. The use of CFD makes it possible to study such particular effects with a good accuracy. Some experimental tests also allowed to verify numerical results and to conclude about the need to modify current Eurocode models.

The flames are described using several parameters characterizing their shape, the temperature, the absorption and the convection coefficient within them. The external flame zone is by convention the area of space outside the room where the temperature exceeds 500 °C. The temperature is supposed to be constant through the section of the flame and the absorption and convection coefficients are supposed to be constant within the flame. Although the absorption coefficient depends on the nature of fuel and on the conditions of ventilation, the use of a value close to 0.3 is recommended. The convective coefficient is based on the heat release rate of the fire and the dimensions of the structural element.

3.2.2.1 Effect of opening

The opening has an effect on the incoming air flux as well as external flames characteristics (dimensions and temperature inside). The multi-openings configuration is of interest because many buildings present such openings.

Several CFD simulations have shown that the incoming air flux can be estimated by the classical approach

$$\dot{m}_a = 0.5A\sqrt{H} \qquad \textbf{(1)}$$

This relation is only valid when the opening is relatively small compared to the façade. When the opening occupies all the frontage of the burning compartment, it is recommended to multiply the previous result by 0.6. A linear decrease according to the percentage of the opening compared to the facade is proposed. This relation starts from 1 when the opening is 80% of the facade and is equal to 0.6 when the opening occupies 100% of the facade.

The dimensions of external flames also depend on the shape of the opening. CFD simulations have shown that the current approach used in Eurocode seems acceptable to estimate flames dimensions from opening ones, even in transient conditions.

On the other hand, the temperature distribution along the axis of external flames is not strongly modified by the opening width in CFD calculations, contrary to the Eurocode assumption.

The multi-opening configuration seems correctly taken into account in Eurocode model when the openings are similar in shape and located at the same level. This is not so obvious when very different openings are involved. In this case, it is difficult to provide an estimation of the external flames characteristics. The use of a zone model is then recommended, in order to know the condition of ventilation for each opening.

A test series performed by TNO has also been used to validate the trends deduced from the numerical simulations.

3.2.2.2 Effect of fuel

The fuel has obviously an important effect on external flames. Firstly, the fuel release rate resulting from the pyrolysis of the fire load has a determining influence on the quantity of unburnt fuel gases leaving the room through the opening. So, the external flames closely depend on that parameter. Secondly, the nature of the fuel can play an important part on the characteristics of external flames.

The effect of fuel release rate is significant on incoming air mass flux by reducing it. The recommended correlation is then

$$\dot{m}_a = 0.5A\sqrt{H} - 0.5\dot{m}_{fuel} \qquad \textbf{(2)}$$

This outcome can be important only if the fuel release rate takes very high values compared to the opening factor.

The main effect of fuel release rate on external flames is to increase their length. It is useful to introduce the global equivalence ratio (GER):

$$GER = r_{fuel/air}\frac{\dot{m}_{fuel}}{\dot{m}_{air}} \qquad \textbf{(3)}$$

This ratio represents the amount of fuel produced by pyrolysis in comparison with the amount of incoming air into the room. It is theoretically greater than 1 when the fire is ventilation controlled. It is theoretically lower than 1 when the fire is fuel controlled. When the GER is unity, combustion takes place in stoichiometric conditions. CFD calculations and current Eurocode model are in relatively good agreement to conclude that the overall flames length is linked to the GER by a linear relation. This can be written

$$\frac{X}{h} = \max[0.5 \quad ; \quad 1.65 \cdot GER + \frac{\sqrt{\max(0;T-800)}}{40}] \qquad \textbf{(4)}$$

X is the length of the flames, h is the opening height and T is the average temperature within the room. Other dimensions such as flames width or flames depth (horizontal projection) are assumed to be correctly estimated by current Eurocode model. In other words, the latter expression can be converted into an expression for the flame height above the upper part of the opening.

The temperature along the axis of the external flame takes a different form according to the GER. The Eurocode model gives coherent results only for relatively high values of GER. When the GER is low, the temperature decrease approaches the results corresponding to external plumes without strong flames. The temperature decreases like power -1 of the position on the axis. When the GER is more important, the decrease follows rather a power -1/2 law.

To conclude, the Eurocode correlation concerning temperature along flame axis seems realistic only for ventilation controlled fires, for which the GER is much greater than unity. During the growing phase of the fire, this relation underestimates the decrease of temperature.

According to the numerical results, it is recommended to use the modified relation

$$T_z(l) = T_a + (T_{f,0} - T_a)(1 - 0.027\frac{l \cdot w}{\max(\dot{m}_{fuel};\dot{m}_{fuel,st})}) \qquad \textbf{(5)}$$

In this relation, $\dot{m}_{fuel,st}$ is the fuel flow rate corresponding to a unit GER.

The distribution of the fire load has been investigated using CFD. Numerical simulations have been performed in order to assess the effect of the localization of the fuel emitting surfaces on the external flames. Several configurations have been studied and are presented in annex 1. The conclusion drawn from this work is that it is possible to systematically place the fire load near the opening in order to predict external flames characteristics. This assumption seems to lead to safe conditions for external elements. This is interesting especially when the compartment is very large compared to its opening. It will be shown further that it is also possible to reduce the size of the compartment in such case. Thus, it might be possible to extend the application of results from cubic compartment to long enclosures having the same opening. So, the conclusion drawn about the fire load distribution is important when dealing with large compartment.

Most often, experimental tests for the study of external flames use wood cribs as fire load. However, there is an increasing use of plastics for furniture or coatings. So, we might wonder about the effect of the nature of fuel on the characteristics of the produced flames. It is well known that a fire can reach higher reaction rates with a non cellulose fuel than with wood cribs. Plastics can continue to produce combustible elements, even in a very fuel rich environment. In order to study the effect of the nature of the fuel, several numerical simulations have been performed. The conclusion of this work is that the use of the global equivalence ratio makes it possible to estimate external flames length in the same way for non cellulosic fuels or for wood cribs. Indeed, the correlation between GER and flame length remains quite unchanged. The nature of the fuel has an influence on the amount of air incoming into the room. The consequence is that higher heat release rates inside can be achieved with fuels having high stoichiometric ratio. The average temperature is thus higher and the external flames seem longer because they are defined by temperature.

3.2.2.3 Effect of compartment characteristics

The study of modern buildings raises the problem of the fire development in large enclosures. This configuration thus constitutes an important case usually met in practice. Two different effects have been numerically studied here: the case of a long compartment and the case of a wide compartment. Comparisons have been made with a reference cubic shaped compartment. The dimensions of that latter compartment are linked to the dimensions of the opening.

It appeared that the problem is not the same for the two configurations. The long, corridor-like, compartment leads to external temperature field very close to the temperature field resulting from the cubic shape compartment. The flows are also very similar between the two compartments. The entering air can’t reach the rear of the long compartment, due to a strong recirculation established there. Indeed, it seems that all combustion processes take place near the opening for the long compartment, quite at the same location as for the cubic compartment. So, we can conclude that the depth of the compartment has no sensible effect on external fields. These calculations show that in these cases the external conditions are very lightly related to the compartment geometry.

In the wide compartment, the situation is somewhat different. It seems that the entering air manages to reach side volumes more easily. It results in a better mixing especially in the upper part of the compartment, which suggests that the temperature field is relatively homogeneous there. A reduction of the flame length has been shown, mainly due to the difference in average temperature of gases contained in the compartment.

By combining the results concerning the distribution of the fire load with the present results, the following conclusion can be drawn. The geometry of the compartment has a different influence according to the width on depth ratio. The long compartment leads to almost the same external flames as an equivalent cubic shaped compartment, whatever the distribution of the fire load on the ground. The configuration of a wide compartment is more complicated. It leads to truly three-dimensional flows, which involves more important thermal losses because the exposed surface to hot gases is increased compared to the cubic compartment. In all the cases, it seems that the characteristics of the flames emerging from the cubic compartment leads to slightly overestimate thermal actions to external members. This observation is important because it makes it possible to justify the use of an equivalent compartment of reduced size for the analysis of large buildings.

The effect of wall thermal properties has also been investigated. Two numerical simulations have been exploited with two values of thermal conductivity in order to study the influence of the thermal losses through the walls on external flames characteristics. Obviously, the wall thermal properties result in a different average temperature within the room.

This study has shown that the length of the external flames follows well the linear dependence with the GER already established, whatever the properties of walls. The effect of increasing the temperature of gases contained in the room thus results in a lengthening of the flames. So, the corresponding curve is only translated. It is noticed that the values estimated by Eurocode model are comparable with the simulations results but they seem a little bit under estimated in the case of insulating walls.

3.2.2.4 Effect of external obstructions

Two kinds of external obstruction have been studied. The first one is the presence of a prolongation of the facade above the opening, whereas the second one is the presence of a balcony. The prolongation of the facade above the opening exerts an influence on the flames shape by restricting the air entrainment into them. So, the horizontal projection is strongly modified. The flames are brought back to the facade when there is a wall above the opening, whereas they extend more easily without this wall. This behaviour has been reproduced by numerical simulation and results are in relatively good agreement with current Eurocode model. The main conclusion is that the shape of the external flames depends on the opening geometry mainly when there is a wall above.

The presence of balconies is also an important parameter to take into account. It is assumed here that the balconies are fire proof and completely prevent the flames to circumvent them on both sides. The simulations have shown that, in the presence of a balcony, the temperature decrease along the flame axis is modified, contrary to the recommendations of Eurocode model. Indeed, it seems that the temperature remains roughly constant below the balcony. The behaviour of the external flames at the edge of the balcony seems to be similar to the behaviour of external flames without prolongation of the frontage, whereas the Eurocode model suggests that the flame "pulls back" over the balcony slab towards the wall of the building. The agreement between Eurocode model and CFD concerning flame length seems to be sufficiently good, and also the temperatures seem to decrease very quickly after the hot gases are released from under the balcony and reach the level predicted by Eurocode model at the end of the flame. Only the balcony's lower surface is subjected to higher temperatures than those predicted by the Eurocode model, which places it on the unsafe side for this case. However, on the basis of the available data, it is difficult to make a very accurate estimate of the temperature under the balcony in all practical cases. Therefore a suggestion was formulated so that it will lead to conservative results. It consists on keeping the temperature constant below the balconies (see annex 1).

3.2.2.5 Effect of wind

Almost all buildings are subjected to non negligible wind speeds in normal conditions of use. The interaction of the flows generated by wind with the roughness of the ground modifies the velocity field close to the ground by reducing its intensity. On the other hand, the openings located high are likely to be subjected to more important winds. With the presence of strong winds, the external flames are deviated and stretched by the external flow. There is also an effect on the existing flows through the opening of the compartment, which can have an influence on the combustion reactions inside.

An experimental study of wind affect has been carried out by CTICM. A series of six tests using different wind speeds have be performed using natural wood cribs fire in a compartment. These tests have allowed investigating the effect of wind on external flames shape as well as on heat release rates achieved within the compartment. The heating and cooling of columns located outside the room as a function of wind speed have also been emphasized.

A complementary numerical study has revealed the main features observed during the tests. In particular, the effect of external flow on the velocity field at the opening has been highlighted. Indeed, it seems that the forced flow restricts the air intake in the compartment, and thus disturbs the mechanisms of combustion within it. So, the blowing significantly restricts the heat release rate of the fire. This point has been established experimentally and numerically.

In fact, the existence of a cross-wind involves a significant disturbance of the flow of air entering the compartment which can certainly modify the fire development. Consequently, the heat release rate of the fire may be less important. This would lead to less severe conditions outside the room. In addition, the cooling of the external elements by convection seems enhanced by the wind.

Finally, it appears that only low speeds of cross-wind have a little effect little on the fire. So, the choice a low wind speed constitutes a priori a safe assumption. In this case, the effect on external flames shape remains moderate. Thus, it seems that the approximation of a deviation of 45° made in the Eurocode model is sufficiently safe, even it is not fully realistic. As it has been shown experimentally, the flame shape should be larger than the width of the opening. Thus the 45° deflection allows taking into account the oscillation of the flame geometry around the average width which is equal to the opening width according to the eurocode model.

3.2.3 Development of a simple model for predicting thermal actions to external structure

The conclusions taken from the previous studies can be incorporated into a simple global model aimed at predicting thermal actions to external structures. An important objective of this new simplified model is to be able to deal with the problem in its transient stage.

3.2.3.1 Simplifying assumptions

Some assumptions have to be done in order to simplify the approach.

- Firstly, the transient problem is treated as a succession of steady state problems. This assumption presents the advantage to allow the use of parts of the existing Eurocode model.

- Secondly, many concepts from current Eurocode model are reused. Particularly, the flame is seen as a radiant solid and the heat fluxes resulting from the flames are estimated via the calculation of a view factor.

- Thirdly, the fuel release rate has to be arbitrary designed and thus requires some hypothesis. As explained in annex 1, the choice of a design fuel release rate is not the same for an internal element as for an external one. It seems that the value of the fuel release rate is not straightforward for an external element and that different calculations using different values are required to find the worst configuration. The maximum realistic value for wood cribs corresponds to a value of the global equivalence equal to roughly 1.5. So, the user has to find a design value of GER between 1.0 and 1.5.

3.2.3.2 Strategy

On the basis of the Eurocode model, there exist many ways of conceiving a method taking into account of the concept of duration of the fire. The strategy retained here is to use zone modelling to more accurately estimate the average temperature within the room and to calculate flow rates through the openings. So, the global equivalence ratio can be estimated, from which flames dimensions can be deduced. The evolution of the fuel flow rate versus time follows an arbitrary law. It is supposed that the growth of the fire follows an arbitrary law until the GER reaches a fixed value, e.g. 1.5. After that, the fuel flow is adjusted so that the GER is maintained at this value. Then, this situation holds until the fuel is exhausted.

Three stages are thus involved in the present global model: the zone model for the compartment fire, the external flames model, and the thermal actions calculation.

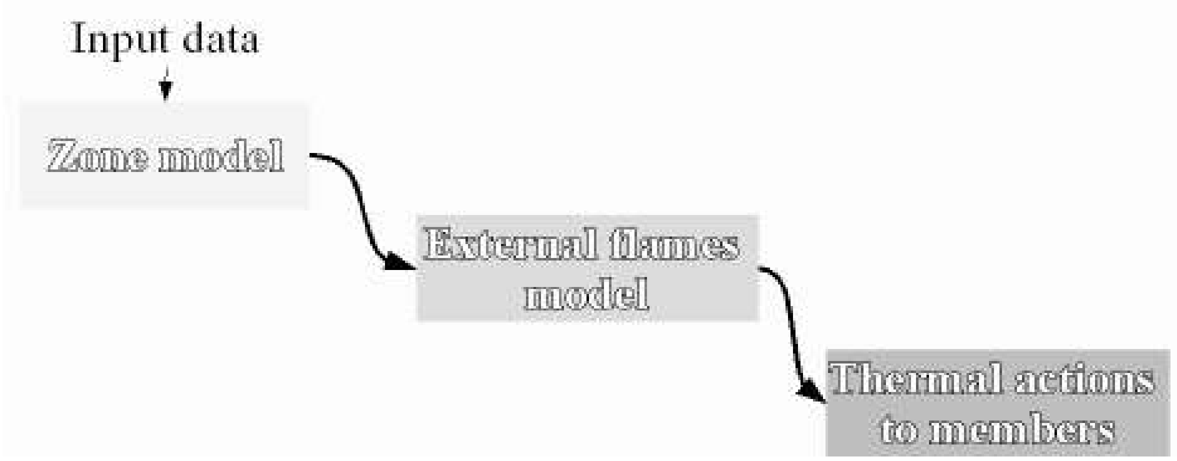


Figure 7 - Main steps in the global model

3.2.3.3 Sub models description

3.2.3.3.1 Zone model for compartment fire

Any zone model able to simulate fully developed fire can be used to estimate the evolution of the temperature within the compartment. This model should allow calculating the GER and the flowing rates through the opening.

3.2.3.3.2 External flame model

Concerning the external flames description, the Eurocode model can be used with the following arrangements:

The overall length of the flames X is given by the correlation (T in °C)

$$\frac{X}{h} = \max[0.5 \quad ; \quad 1.65 \cdot GER + \frac{\sqrt{\max(0; T - 800)}}{40}] \qquad (6)$$

This value is then employed to calculate the flame height above to top of the corresponding opening.

The temperature along the axis of the flame follows the relation

$$T_z(l) = T_a + (T_{f,0} - T_a)(1 - 0.027 \frac{l \cdot w}{\max(\dot{m}_{fuel}; \dot{m}_{fuel,st})}) \qquad (7)$$

In this expression, $\dot{m}_{fuel,st}$ is the fuel flow rate corresponding to a unit GER.

3.2.3.3.3 Heat flux calculation

The Eurocode approach is conserved. The calculation of heat flux is done by considering the view factor between the solid flame and the considered target. As a first approximation, parallelepipedal shapes from Eurocode model flames are reused.

3.2.3.4 Global model validation

A comparison between model predictions and experimental measurement is given in annex 1. This comparison shows that the simplified model achieve a relatively good agreement with experimental data despite its simplicity. This work also reveals that an error on the flame dimension can obviously have a significant effect on local temperature value.

On the whole, it is interesting to note that the current Eurocode model can be used in transient state without much modification of its sub-models.

3.3 Steel structures exposed to unconfined localized fire

Responsible partner: ARBED	**Other partners:** TNO
Objectives: *Development of temperature calculation for internal steel structural elements exposed to localized fires.*	

There are two methods in Annex C of EN 1991-1-2 which can be used to estimate temperature in steel beams. These models calculate in fact the gas temperature or the heat flux at a certain distance to the fire. This can then be employed to obtain the temperatures in a steel member via its section factor, by means of simplified method aimed at predicting its heating.

The first method can be used when there is no ceiling above the fire. It allows one to calculate the temperatures at different height in the centre of the fire. The second method is based on the experimental tests performed by HASEMI. With this method, one can calculate the heat fluxes under the ceiling in function of the distance to the fire.

The problem is that none of these methods are usable to calculate the temperatures in a different height and a different distance to the fire, what would be needed to calculate the temperatures in a column exposed to a localised fire. To circumvent the problem, an approximation is often made with the HASEMI method, by decreasing step by step the height of the ceiling and obtaining by doing so the temperature at different heights. But this seems to be a quite conservative estimation, and PARE tried therefore to establish a new simplified method, allowing calculating the temperatures in a column.

Firstly, to develop such a method, the CFD code SOFIE has been used as a numerical tool. Several simulations have been done in order to calibrate the CFD code. In a first approach, a test performed by BRI involving a steel element exposed to a steady localized fire has been simulated and results have been compared to the measurements. Secondly, it was tried to calibrate CFD with an additional localized fire test performed in a large compartment by CTICM.

The comparison showed that test and simulation results were not in very good agreement. So, the confidence in the CFD tool was though to be not high enough to be used for the development of the method. Furthermore, the computer times required for the simulations have been relatively high and the number of tests to be used for the calibration has not been sufficient. This CFD investigation is further explained in annex 5.

Thus, it was preferred to use the different methods given in the Eurocode 1 and 3, and to combine them in such a way that the temperature of a column, affected by a localized fire, could be calculated in function of the height.

The calculations presented in annex 5 are based on the methods described in Eurocode 1 Part 1-2 and Eurocode 3 Part 1-2. The objective is to estimate the time evolution of the temperature distribution within the column. The model has to be able to cope with multiple fires of which rate of heat release is evolving, following an arbitrary law defined by the user. The fires can be positioned anywhere around the column. The objective is achieved in several stages. Initially, a single fire of constant RHR, placed anywhere around the column, is considered. The fire is modelled as a single radiating surface of constant temperature, taken as the temperature at the flame mid-height. This simple model can be made more complex by considering a layered fire structure (with different temperatures at different heights), fires with changing rates of heat release, and by using multiple fires. This work is explained in annex 5.

The conclusion of that study is that the use of Excel Macro is resulting in too long calculation times. This problem could be solved by programming the model in FORTRAN for example. Furthermore, the capability of the model could be improved by dealing with the case of a fire engulfed column. Shadow effects could also be accounted for in the configuration factor calculation, rather than with a parameter in the temperature calculation formula. When using pyramidal flame model, the height of the top layer could be chosen automatically according to some criteria that have still to be defined.

3.4 Thermal response of bare and composite steel structures

Responsible partner: LABEIN	**Other partners:** ARBEB, CTICM,TNO
Objectives: *Development of temperature calculation methods for bare and composite external elements.*	

The current Eurocode model of heat transfer to external steel structures is depicted in the annex B of the EN 1993 – 1 – 2. This model takes as simplified inputs flame shape and properties which are defined in the annex B of the EN 1991 – 1 – 2. The main features of the heat transfer model to external steel structures are the following:

- It uses steady state approach: there is no time evolution of the temperature.
- The calculation procedure is different in case of the profile being engulfed or not, to account for the differences in heat transfer due by radiation and convection.
- It considers a constant temperature within the section.
- Heat flux is calculated on a bounding box around the profile. Therefore shadow effects are not accounted for.
- Composite sections are not considered.

So, a new model has been developed to tackle with these limitations. The proposed new model features are:

- Transient calculation method allowing calculating temperature time evolution.
- For open sections, it is allowed to calculate heating of webs and flanges independently.
- For open sections, it is allowed to consider shadow effect in the heating of webs and flanges.
- It is also allowed to calculate radiation heat transfer between parts of the sections (flanges and webs)

3.4.1 Model description

The model is based on the current model of Eurocode 3 with some modifications. For example, heat transfer within structural members is treated as a 2D calculation.

The radiation from the fire compartment is calculated using the fire compartment temperature evolution. The openings are considered as emitting surfaces at the temperature of the fire compartment and a view factor need to be calculated. One of the main new features of the present model is the ability to account for shadow effect in open sections concerning radiation from openings and, for not engulfed members, concerning radiation from flames. Indeed, in the Eurocode model, heat flux is simply calculated on four sides of a bounding box around the profile. In the present model, radiation heat transfer is calculated from any emitting surface to the part of the receiving surface that effectively receives radiation, by considering shadow effect. Hence, radiation is calculated in every face of the parts of the open section.

It was shown by calculations that supposing that the whole radiation on the web or flange is estimated by calculating the radiation received at the mid point instead of a series of points on it is a fair assumption. So, the hypothesis of a simple point analytical method was acceptable, because the results provided by that model are not very different from the results provided by more complex models.

Other modification of current Eurocode model is that the present model is able to take into account radiation exchange between every surface (web and flanges). This refinement can be of interest for non-engulfed members, when exposed flanges are exposed to much higher radiation fluxes than web and non-exposed flange, leading to a redistribution of heat within the steel section enhanced by radiation.

The temperature evolution of webs and flanges is then obtained at every time step, by using the expression from Eurocode 3 aimed at calculating steel temperature evolution as a function of heat flux.

3.4.2 Model validation

The present model was implemented into a computer code, in order to make it easier to use and to be validated against experimental data. An extensive use of this code has been done to validate the model. The validation has been done for both open and composite sections (hollow sections filled with concrete).

For open steel sections, the model predicts temperatures of webs and flanges which can be directly compared with test results. For hollow sections filled with concrete, the model predicts heat fluxes on 4 points of the steel section. Hence, a finite element analysis has been done with the non-linear finite element analysis code SAFIR.

For composite sections, it was intended to assess two assumptions concerning heat transfer within the section, on the basis of experimental tests data:

- The application of the conclusions drawn up in a previous research (ECSC N° 7210 PR 380 N.98) about the effect of air gaps between the steel section and the concrete core once heating begins.

- The possibility of reducing a complex 2D finite element analysis to a 1D analysis considering for every section the portion of it affected directly by the heat flux.

Three different ways of defining the flame and compartment properties have been considered:

- Quasi-steady state approach.

- Use of a zone model.

- Use of direct application of test observations.

For open sections, the temperature curve shape is in good agreement with the experimental one and the model yields results in the safe side by comparison with the test results. The best agreement between the test and the model results is obtained closer to the façade. On the whole, 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. Some discrepancies are found but they not due to the heat transfer model but rather to the introduction of thermal action, because some assumptions of the current Eurocode model deemed to be too conservative are kept.

For hollow sections filled with concrete, the inclusion of the air gap always leads to higher temperatures in the steel profile due to its insulating effect. Therefore it is not recommended to include such air gap in the calculations. The 1D model yields conservative results in terms of steel temperature if the analysed point is submitted to the highest heat flux, because the heat transfer by conduction to the rest of the composite profile is not accounted for.

3.4.3 Conclusion

To conclude, the calculation of the steel temperature for open sections is made by considering the flanges and web independently accounts for thermal gradients within the sections. This phenomenon has been often observed during fire test of external steel members. The model is based on 3D geometries for definition of configuration factors, but a 2D (reduced to 1D within the sections) calculation is performed (no conduction along the profile axe is considered). For composite sections, due to the low conductivity of concrete, larger gradients occur, and a finite element calculation is addressed after calculation of heat fluxes on 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 hottest point of the section, because it neglects the conduction to colder parts of steel perimeter. Otherwise, if a full description of temperature rise is of interest, it tends to underestimate temperature rise of coldest points. This leads to an overestimation of thermal gradient within the section. If the bending moment induced by this thermal gradient sums up to the initial bending moment this result is not unsafe, otherwise, in the first stages of the fire exposure, it leads to a reduction of the actual bending moment acting on the member. This effect may be neglected once high temperatures are reached within the section so that accidental induced actions do not play the main part in collapse mechanism.

3.5 Thermal response of protected steel structures

Responsible partner: CTICM	**Other partners:** ARBEB, VTT
Objectives: *Development of temperature calculation methods for protected external elements.*	

3.5.1 Introduction

The WP3 is intended to develop a model aimed at calculating the temperature of protected external elements. Particularly, the case of interest is sections insulated by protection materials such as intumescent coatings.

This work package also contains a method designed to obtain equivalent thermal characteristics of intumescent coating, on the basis of test using conventional temperature curve. These values can then be reemployed under natural fire conditions for external members to predict their heating. All the results are shown in the appendix 3 report.

3.5.2 Use of intumescent coating

According to the study done in WP3, one can say that the use of intumescent coating for the protection of external elements has to fulfil the following conditions:

- It has to be tested in order to know its fire resistance according to the European ISO Fire testing conditions described in the ENV13381-4 for steel elements.
- It has to be submitted to aging test with different weather conditions.
- The fire resistance according to the European ISO Fire testing conditions described in the ENV13381-4 for steel elements has to be checked, using the intumescent coating that has been employed during the aging tests. The resulting performance has to be almost as good as the initial fire resistance test.
- A natural fire tests with external elements has to be done to ensure that the intumescent coating behaviour is acceptable with such kind of thermal actions.

3.5.3 Determination of equivalent thermal properties

Once the ability of intumescent coating to protect external members is verified, the equivalent thermal properties can be determined with:

- The assumption of an equivalent thickness equal to 10 times the real applied thickness.

- The determination of the thermal properties using comparison with the:

    - ISO Fire test results.

    - Natural fire test results for external use.

There are several methods used to evaluate thermal properties, mainly based on a comparison between the measured times to reach a certain design steel temperatures and calculation results. The various assessment methods differ in the way the time to reach a certain design steel temperature is determined. Nevertheless, the application of these ones is restricted to the context of standard fire. So, these thermal properties are not valid for external structures.

The methodology developed by CTICM to have a better characterisation of thermal properties of the intumescent materials is based on a parametric numerical study, using a finite element code. The varying coefficients are the thermal conductivity and the specific heat. The principle of the parametric study is to compare experimental and numerical results concerning temperature. This study permits to determine the thermal conductivity and the specific heat of the intumescent product in order to obtain a good correlation with all the experimental results. The conditions under which these characterisations were carried out correspond to the normalized fire ISO 834. In order to take into account the expansion effect of the intumescent coating during its heating, the method assumes that the thickness of the coating is 10 times its initial value.

3.5.4 Validation

The numerical simulations are in good agreement with the thermocouple measurements, in particular during the heating of the element. However, the cooling effect is not well simulated. But the focus is not put on the decay of the fire. The maximum temperature and the time to reach it are the main parameters.

The following figure gives an example of comparison between prediction using equivalent thermal properties and experimental data.

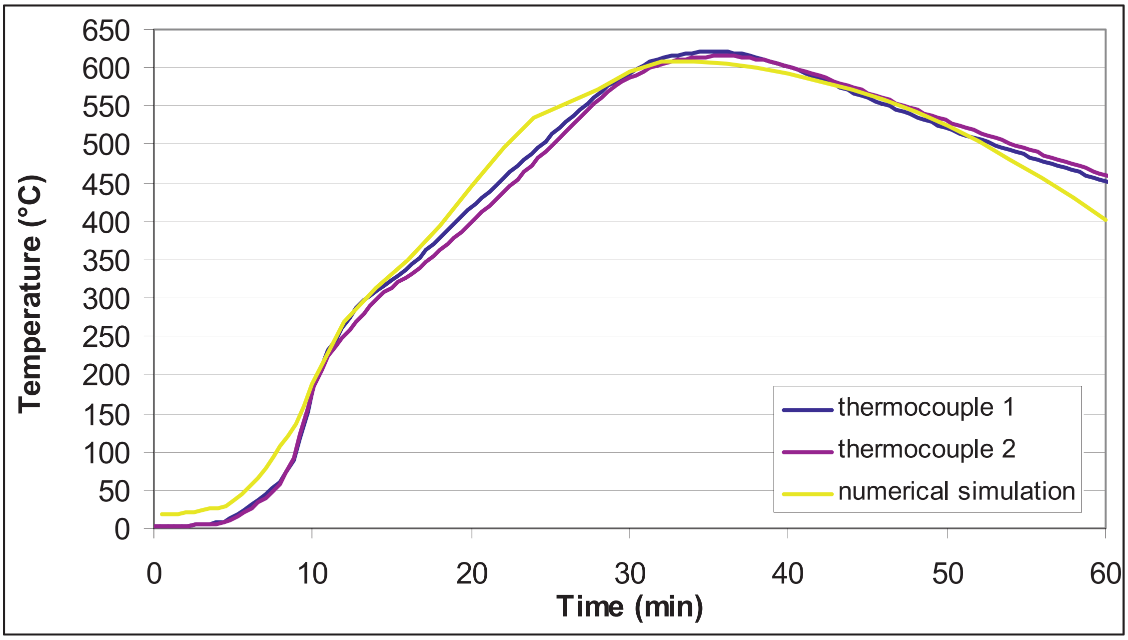


Figure 8 - Example of validation against experimental measurement

3.5.5 Conclusion

This approach has been applied with two different intumescent coatings. The agreement with experimental results is fair. The method managed to estimate the heating of insulating members in natural fire conditions. It can then be used to determine the thickness of protection that have to be applied on external steel elements to ensure their fire resistance.

3.6 Thermal response of encased structures and balconies

The objective of this work package is to develop temperature calculation methods for external steel structural elements shielded by mild or stainless steel encasements, and balconies. Experimental tests on structural elements under temperature loads have also been carried out within the framework of this work package. The following paragraphs summarize the work done by VTT during the present research. More details are given in the appendix 4 reports (part A for the encasement solutions, and part B for verification of balconies).

3.6.1 Experimental tests description

3.6.1.1 Encased elements

A total of five large scale fire tests were carried out at VTT. All tests were performed in order to evaluate the thermal transfer from flames and hot fire gases to unprotected or protected steel columns. Six different column setups were considered. One fire test was carried out as a reference test using the Horizontal furnace at VTT and the EN 1363-1: 1999 standard fire curve. The other four tests were carried out using the VTT façade test rig and natural fire conditions. The tests provided valuable data on the temperature development of steel sections subjected to different heating conditions.

3.6.1.2 Previous tests concerning balconies

No tests were carried out on balcony structures in the frame of this project but, instead, balcony tests carried out previously at VTT were used as the basis for the development of a simple calculation method for the heat transfer through balcony slabs.

3.6.1.3 Previous tests concerning steel emissivity

A small test series for the evaluation of the emissivity of stainless steel was carried out. The research was done in connection with a larger NORDTEST research project that has been reported in the publication VTT Research Notes 2299 by T. Paloposki and L. Liedquist. The findings of the project can be directly used in numerical calculation work.

3.6.2 Numerical simulations description

Responsible partner: VTT	**Other partners:** CTICM, LABEIN
Objectives: *Development of temperature calculation methods for external steel structural elements shielded by steel or stainless steel and balconies.*	

Numerical simulations in two and three dimensions were carried out using two different finite element packages: FEMLAB (currently called COMSOL Multiphysics) and ABAQUS/Standard. The FE-analyses were mainly based on the tested sections in different heating conditions. The results of the analyses were deemed to be satisfactory or very good, depending on the analysed case. Both unprotected steel columns and steel columns protected with different types of encasements were analysed.

Numerical simulations of the heating up of balcony slabs were carried out using FEMLAB with good results. All numerical analyses using FEMLAB and ABAQUS/Standard were used as additional references for the development of simple calculation methods for the thermal development of steel columns and balcony slabs in fire conditions.

3.6.3 Model development description

3.6.3.1 Encased elements

Simple calculation methods were developed for the thermal analysis of steel columns that are unprotected, or protected with thin steel encasements. The developed 1D-calculation method can be used when both the structure and the fire exposure are cylindrically symmetric. This is also valid for RHS-sections, which are not quite cylindrically symmetric. The developed 2D-calculation methods are more general and can be used for CHS-, RHS-, H- and I-sections subjected to either symmetric or asymmetric fire exposure.

The calculation methods were validated against test results and compared to finite element modelling results. The methods were programmed using MATLAB and full instructions for their use have been given.

3.6.3.2 Balconies

A simple 1D-calculation method for the thermal analysis of layered structures was developed. The foremost application of the method is for layered steel sheet balcony slab structures, but the method can be used for any layered structure, which can be approximated in 1D. The method was validated against available balcony test results and finite element analyses. It was programmed using MATLAB and full instructions for its use have been given.

Sensitivity analyses were carried out along the validation processes for all the above calculation models within the essential ranges. Suitable material parameters and modelling practices for the attainment of conservative results were established.

3.7 Methodology for evaluating the heating of external structures

The Eurocode model has been developed on the basis of empirical assumptions. Even if this model is analytical, its use can be done by hand. Different software have been developed in many countries in order to simplified its application restricted to unprotected steel structures from a steady state assumptions.

One aim of the present project was to develop a method for transient condition in order to extend the current model to protected steel structures or composite structures. The results of the method are the determination of the thermal actions from the external flaming to the structural elements. Then, methodology for determination of the thermal response of protected steel structure, composite structure and encased steel structure has been developed.

When application has to be made, the verification of the fire stability for an unprotected steel structure has to be made first.

If the fire stability is not achieved, several parameters may be changed to obtain the required fire stability:

- the section of the structural element should be increased (increasing thus the critical temperature)
- the geometry of the compartment should be modified, and mainly the opening closed to the steel structure
- a protection or a composite section can be involved: then the transient method has to be used:

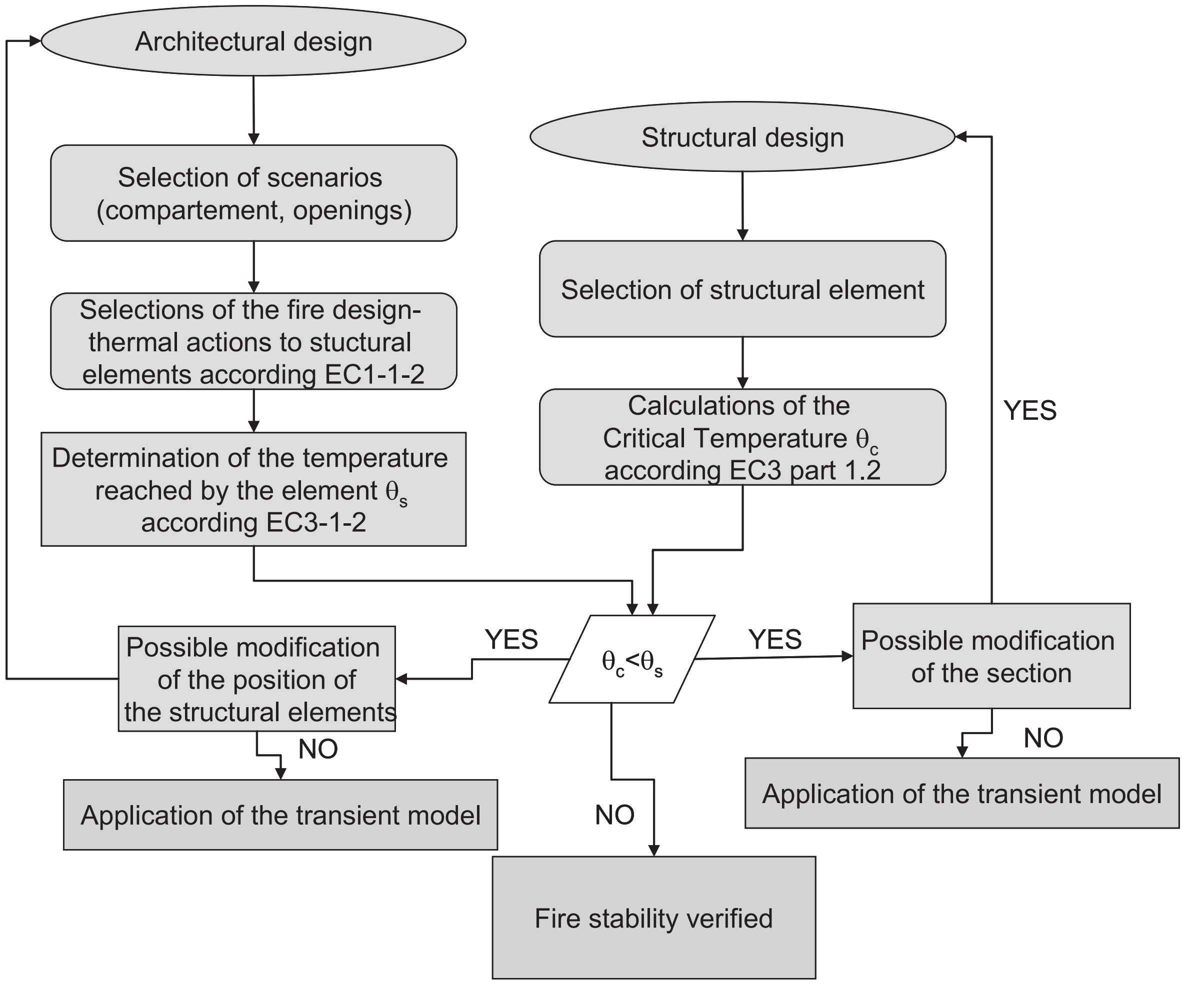


Figure 9 - Steps to verify the fire stability of structural elements using the current eurocode model

An example of application of the method presented in the present chapter is given in the following chapter.

3.7.1 Transient method for thermal actions

The transient method consists on the following steps:

- Step 1 : selecting design fire scenarios and design fires
- Step 2 : determining the thermal actions to the structural elements
- Step 3 : determining the thermal response of the structural elements
- Step 4 : determining the fire behaviour of the structural elements

The two main steps should be summarized by the following graphs giving the main data.

To determine the thermal actions to the structural elements, the first step (1) is similar than the current Eurocode Model. Only additional recommendations have been given, by using two design-fires, the first with a global equivalence ratio (GER) of 1, and the second with a GER of 1,5.

Then from these design-fires, the thermal actions have to be calculated according to the methodology developed in the present project. In fact, three levels of complexity of the method are proposed as mentioned in the following figure:

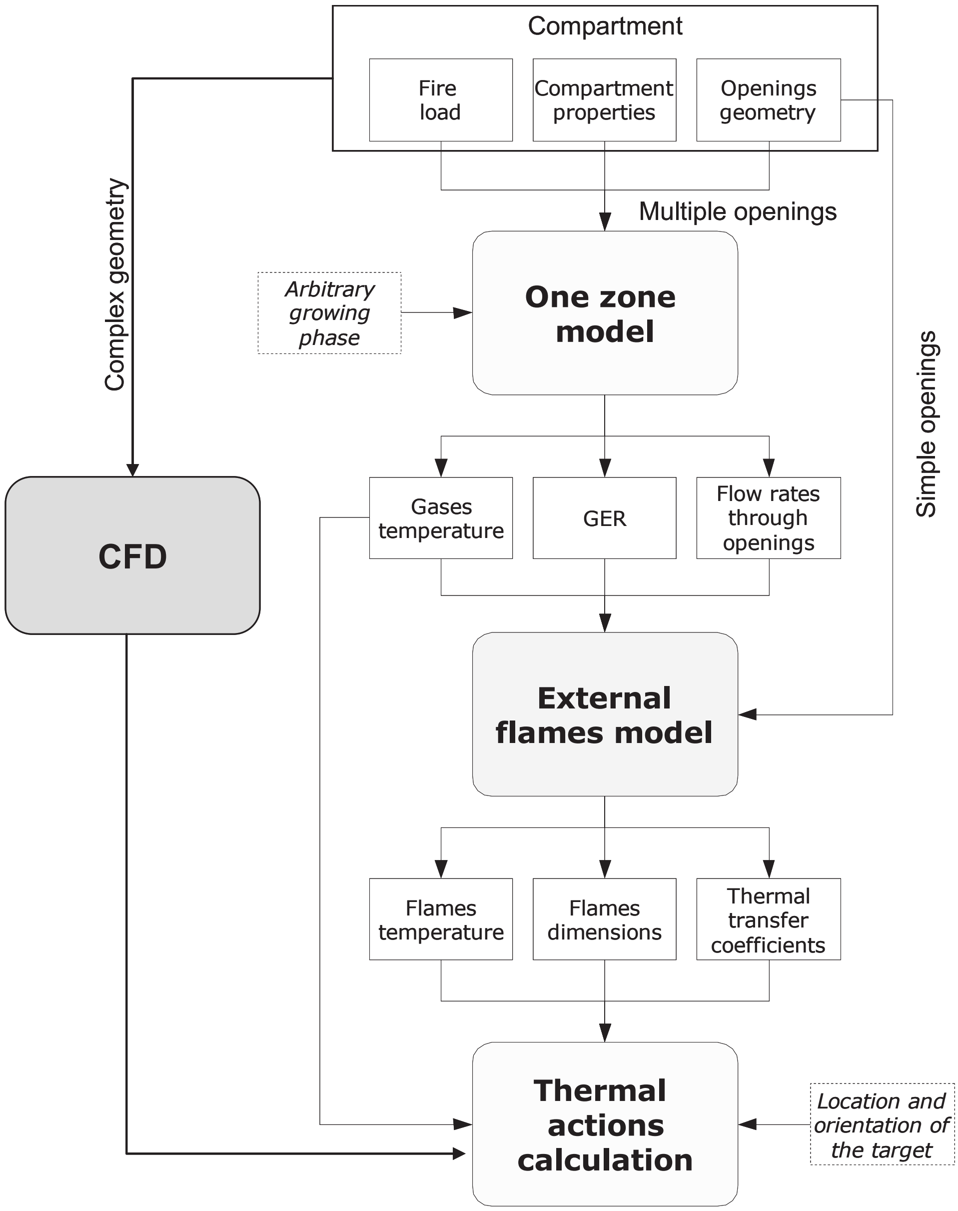


Figure 10 - Strategy retained for the simple model

3.7.1.1 Level 1: simple geometry and openings a the same height

For that level, all the analytical method has to be used. The different equations of the current eurocode model are used with the following modifications:

- Calculation of the pyrolysis rate

$$R = GER\frac{0.5A\sqrt{H}}{r_{fuel/air}} \approx 0.088 \cdot GER \cdot A\sqrt{H}$$

- The overall length of the flames X is given by the correlation (T in °C)

$$\frac{X}{h} = \max[0.5 \quad ; \quad 1.65 \cdot GER + \frac{\sqrt{\max(0;T-800)}}{40}]$$

This value is then employed to calculate the flame height above to top of the corresponding opening.

- The temperature along the axis of the flame follows the relation

$$T_z(l) = T_a + (T_{f,0} - T_a)(1 - 0.027\frac{l \cdot w}{\max(\dot{m}_{fuel}; \dot{m}_{fuel,st})})$$

In this expression, $\dot{m}_{fuel,st}$ is the fuel flow rate corresponding to a unit GER.

- Using balconies needs to use the modification proposed in the present report and in the appendix report 1 (WP1) and appendix report 4 part A describing the effect of a balcony

- Compared to the current eurocode model, shielding effect of the steel profiles may be taken into account using the tools developed in the present research for H or I profiles

- The temperature inside the compartment is given by the parametrical fires of eurocode as a function of time

From these applications, a thermal action is determined. This thermal action is then applied on structural elements during the external flaming duration Te-f that can be assessed by:

$T_{e\text{-}f} = (Q_{f,d}\ A) / (R\ \Delta H_c)$

where

Qf,d is the design fire load (MJ/m²)

A the surface of the compartment (m²)

R the pyrolysis rate (kg/s)

ΔHc is the net combustion heat (MJ/kg)

3.7.1.2 Level 2: multiple opening with different heights

This second level of complexity is the same application as the level 1, but a one zone model is used for:

- determining the temperature-time curve in the compartment with better accuracy than the parametrical fires

- determining the neutral plane to define an equivalent opening according to the conditions of air entrance and external flaming

3.7.1.3 Level 3: complex geometry and specific fluid flows

The third level is relevant to complexity of

- the geometry of compartment

- the structural elements

- the characteristics of the type of protection used (e.g. deflector)

In that conditions the fluid mechanisms can not be simplified, and a complete modelling of the external flaming and its interaction with structural elements has to be made.

Figure 11 - Example of external columns protected by deflectors

Recommendations of the use of the CFD for that verification is given along the report, as for example the use of two main design-fires defined by a GER of 1 for smaller thermal actions with a larger duration, or a GER of 1.5 for larger thermal actions with a small duration.

3.7.2 Thermal response and mechanical behaviour

From the thermal actions as a function of time, the thermal response and mechanical behaviour has to determine.

Methods for the thermal response of the 3 types of elements are given in the present report:

- hollow core steel sections filled of concrete, with or without rebars
- steel sections protected by intumescent coatings
- steel sections encased in a steel box

For the temperature distribution in the profile, the mechanical behaviour can be assessed with the eurocode 3 part 1.2 “fire behaviour of steel structures” or eurocode 4 part 1.2 “fire behaviour of composite structures (steel and concrete), or with a finite element model (FEM) when the temperature distribution is not homogeneous or if the structural element is out of the scope or the application domain of the eurocode.

3.8 Example of application of the methods developed during this project

3.8.1 Introduction

An example is treated now, in order to show an application of the methods developed within the framework of the PR380 project. The case of a real building is used here to show how the simplified methods can be involved to define a solution in a realistic context for which external members have to be protected.

3.8.1.1 Building configuration

The considered building has 9 levels of 2.80 m height. Its facade is made of glazed frontage, so the entire facade of each room can be opened during fire. The level studied here is composed of offices and libraries. Compartment studied in level 1 is 30.0 m width and 23.0 m depth, whereas compartments of level 2 to 4 are 23.0 m on 23.0 m.

3.8.1.2 External members configuration

At each level, the external structure is made of columns (HEB300) linked to parallel beams (UAP270) by perpendicular members (HEA280). A picture of the external structure is given in Figure 12, whereas the location of the members is given in Figure 13. The present application is focused on the column.

Figure 12 - Picture of external members

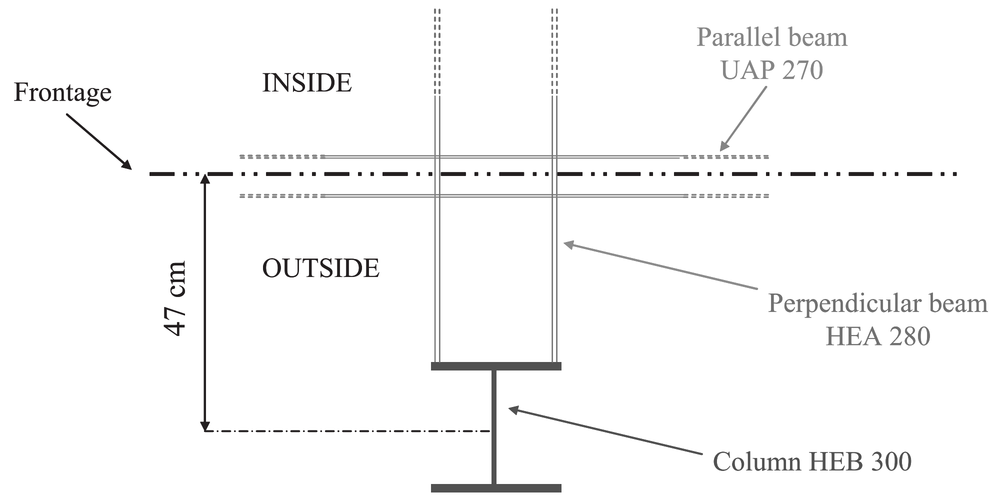


Figure 13 - Location of external members

3.8.1.3 Mechanical loads

The buckling length is Lfi = 2,10 m (0,7 x height 3,00 m). The axial loads are given on the column for both representative levels:

Level	Level 1: Library	Level 2: Office
$N_{fi,Ed}$ (kN)	1 587	1 415

Table 7 - Mechanical loads

3.8.1.4 Critical temperature of the columns

The mechanical resistance of the structure is supposed to be achieved when the temperature reached by each element is below a given critical value. Theses critical temperatures calculated according EN1993-1-2 are summarized in Table 8 below. When the temperature reached by the element is lower than the critical temperature, the fire stability of the structure is verified. The critical temperature is generally compared to the average value of the temperature reached by the element, when thermal gradients in section are not driving the mechanical behaviour of the structural element.

	Level 1	Level 2
Critical temperature (°C)	563	727

Table 8 - Critical temperatures for external members

3.8.1.5 External members temperatures

3.8.1.5.1 Room geometry

A parametrical study has been performed to find the worst opening configuration concerning external members. The conclusion of this study leads to the compartment geometry shown in Figure 14. Two values of fire load density are used: 100 kg/m² representative of the library and 30 kg/m² of wood representative of the office. The member is supposed to be located in the center of the opening: no fire resistance mullion is defined in the building.

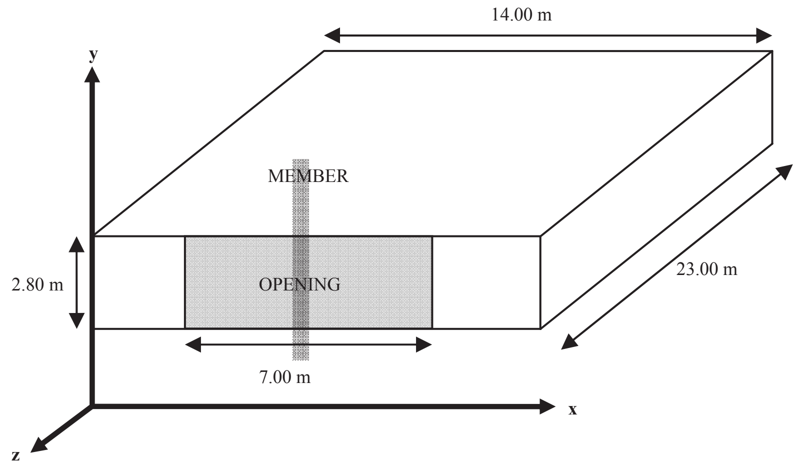


Figure 14 - Overview of the reference compartment

3.8.1.5.2 Heat fluxes to external elements

The application of eurocode model leads to the following results given in table 2. The axes are shown in Figure 14.

	Φx+ (kW/m²)	Φx- (kW/m²)	Φy+ (kW/m²)	Φy- (kW/m²)	Φz+ (kW/m²)	Φz- (kW/m²)	T (°C)
Column	81.2	81.2	0.0	0.0	34.2	88.5	764

Table 9 - Heat fluxes and temperatures reached by unprotected members according to eurocode method (Φz- corresponds to the face facing the opening)

3.8.1.6 Fire stability of unprotected columns

Regards to the critical temperatures and the temperatures reached by the columns according the Eurocode 3 part 1.2, it can be concluded that the columns are the level 3 are fire resistant and could stay unprotected, while the columns at the level 1 and 2 are not and should be protected.

It is then proposed to apply the method and tools developed within the present research to design the protection or chose new column section to be fire resistant, using an unsteady approach.

3.8.2 Application of the PR380 methods to protect columns

3.8.2.1 Estimation of the design HRR curve

The same HRR curve is used for defining every types of protection. The mass flux of air entering into the room is assumed to be

$$m_a = 0.5A\sqrt{H} = 16.4\ \text{kg/s}$$

Using a global equivalence ratio of 1.5, this lead to a fuel mass flux of wood of $m_f = m_a \dfrac{\Phi}{r} = 16.4 \dfrac{1.5}{5.7} = 4.3\ \text{kg/s}$ So, the maximum heat release rate is 60 MW.

Using fire load densities of 100 kg/m² and 30 kg/m², this leads to the curves shown in figure 4. We assumed a t square fire (growing in 1200 s) followed by a steady period and linearly decreasing when 70% of the fire load has been consumed.

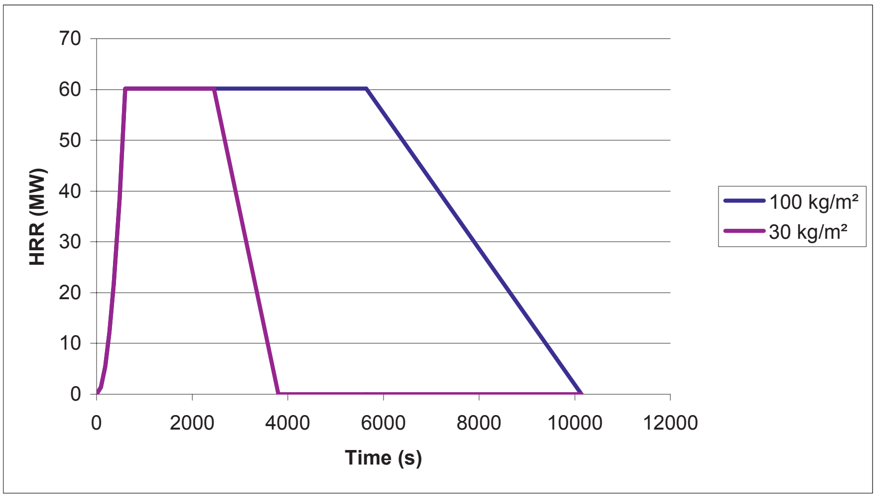


Figure 15 - HRR curves for the two fire loads

From that curves, from the heat flux on each surface of the column is defined by the following heavy side shaped curve as a function of time. The start and the end in each case correspond to the time when HRR is half its maximum value (see Figure 15).

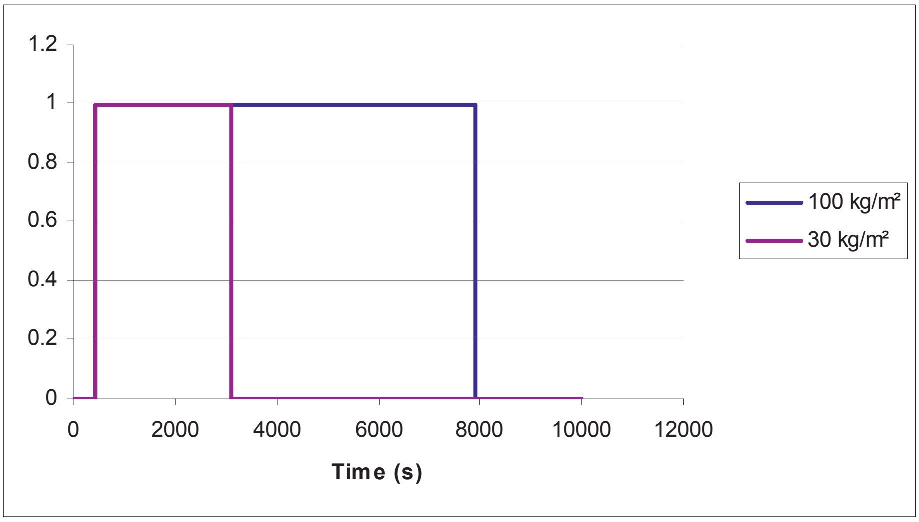


Figure 16 - Heat fluxes curve shapes for the two fire load

The recommended values for maxima are those summarized in Table 9. These heat fluxes are employed for designing the protection of the column in terms of intumescent coating, or steel box, or for designing a composite column.

3.8.2.2 Concrete filled section

In order to calculate thermal actions on the members, the code EXTFIRE developed during work package 2 has been used. The thermal analysis of sections heating for composite columns has been done with the non-linear finite element code SAFIR developed by the University of Liege.

3.8.2.2.1 Compartment fire

A calculation has been performed with the zone model Ozone, using as input the mass loss rate curve defined in the exercise in order to estimate radiation from the compartment. Figure 17 and Figure 18 show evolution of temperatures and mass loss rate curves for fires in both levels. The blue line shows the period of time during which the external flame develops according to the exercise.

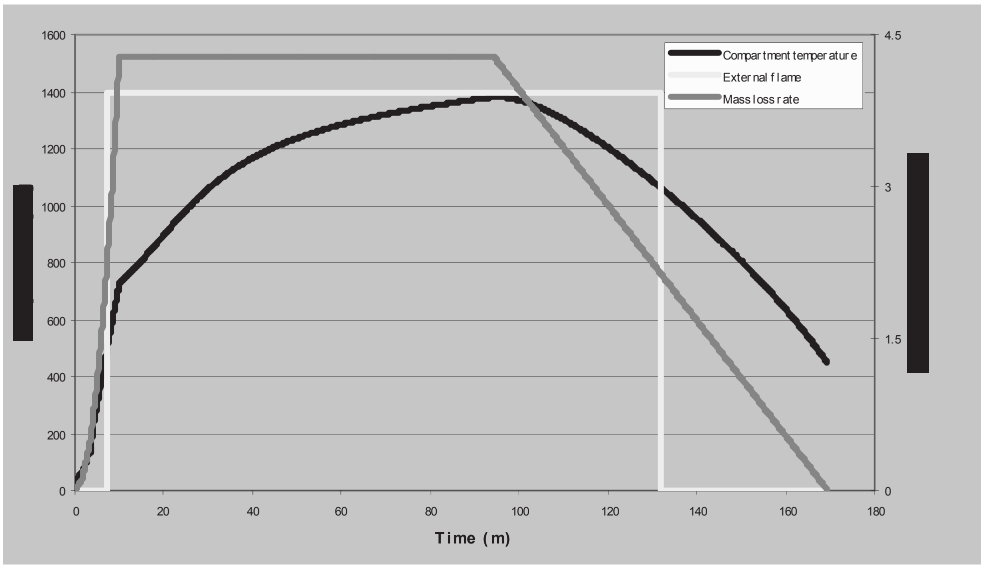


Figure 17 - Temperature of the compartment for fire in level 1

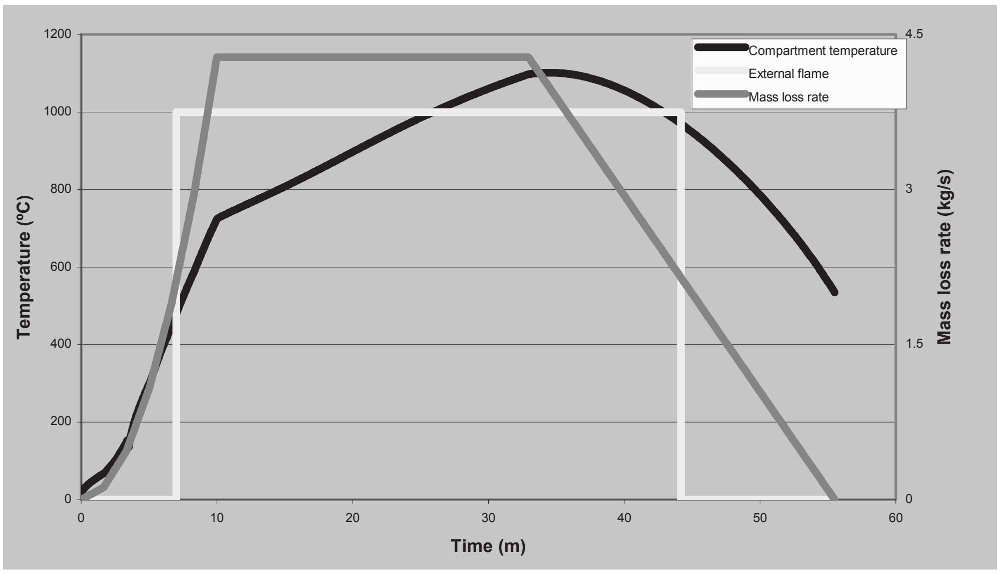


Figure 18 - Temperature of the compartment for fire in level 2

3.8.2.2.2 Results for external members

3.8.2.2.2.1 Level 2: fire scenario in an office

The figure below shows the evolution of temperature within the flanges and web of the HEB 300 profile in front of the office at the height of the soffit of the opening.

The peak temperature in the exposed flange is 576º C. If the Eurocode 3 part 2 is used to calculate resistance of the sections it should be considered the highest temperature of the section. The critical temperature (727 ºC) is higher than the peak temperature, so it results that the columns does not collapse.

The steady state calculated in the exercise (blue line in Figure 19) is much higher than the transient one, above the critical temperature, leading to conservative conclusions. The exposure time is not long enough to make the profile reach the steady state temperature. To summarize, if a transient calculation is done, the profile does not need to be protected with passive protection, because collapse does not occur if the member remains unprotected.

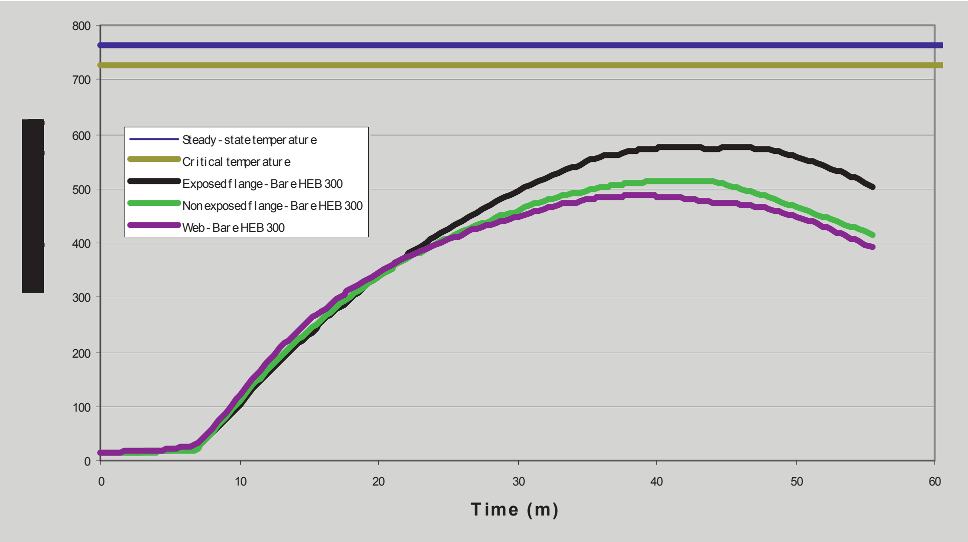


Figure 19 - Temperatures within the HEB 300 profile in front of the office

3.8.2.2.2.2 Level 1: fire in a library

Figure 20 shows temperature evolution in flanges and web of the HEB 300 in front of the library. As foreseen, the critical temperature is reached firstly in the exposed flange at 37 minutes and later in the non-exposed flange and the web. So, a design of composite column is proposed as shown in Figure 21 to provide insulation to the steel section. A concrete partial encasement is proposed only for insulation purposes not for structural resistance. The concrete is made of siliceous aggregate with content of 100 kg/ m3 of water.

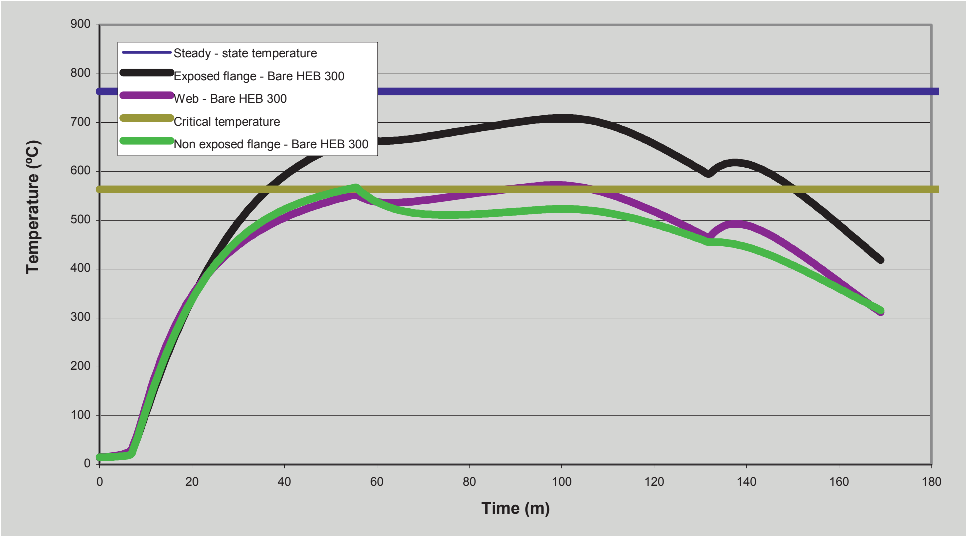


Figure 20 - Evolution of temperature in the bare HEB 300 section for fire in the library

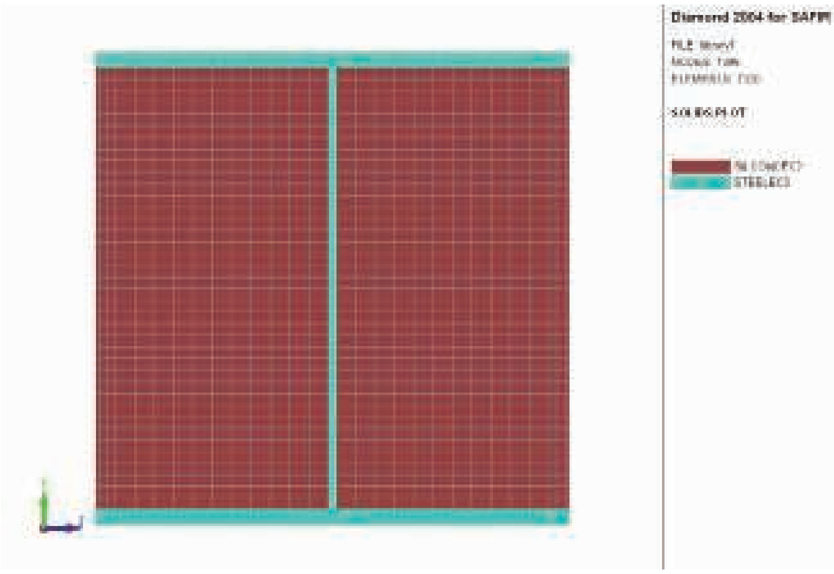


Figure 21 - Composite section design proposed for the HEB 300 section

Figure 22 shows a comparison of temperature evolution in the flanges and in the web for the bare HEB section and for steel in the composite column.

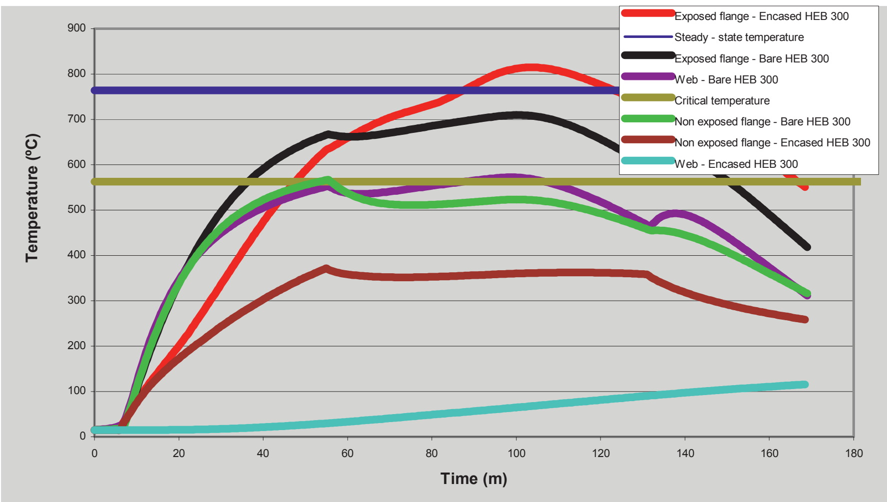


Figure 22 - Comparison of temperature evolution in the steel section

Figure 23 shows a temperature distribution within the section at 110 minutes of exposure when the peak temperature is reached in the exposed flange.

As a result of the concrete insulation, the exposed flange undergoes an increase of temperature by comparison with the bare section. This is due to the fact that in the composite section, the concrete core acts as a barrier that hinders the exposed flange to evacuate heat to the rest of the section. However the non-exposed flange and the web reach much lower temperatures in the composite section than in the bare section.

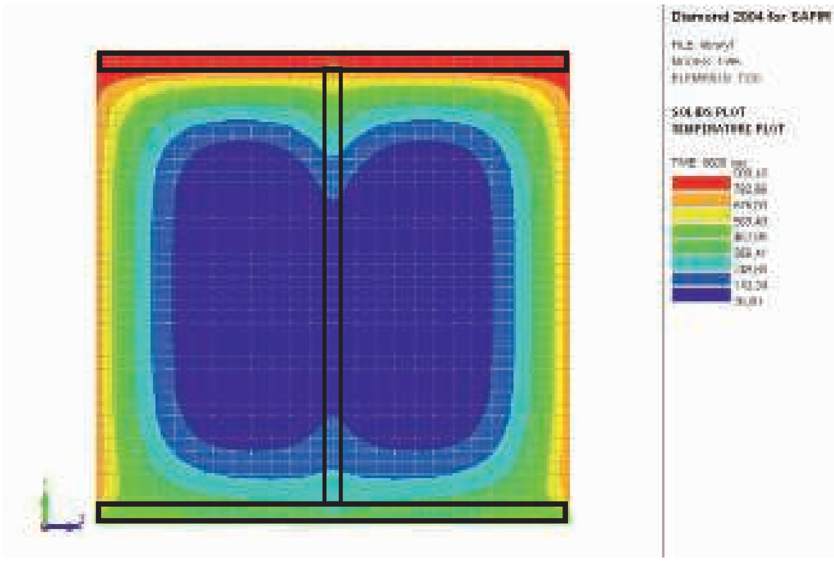


Figure 23 - Temperature distribution within the section at 110 minutes

If the simplified Eurocode 3 rules are used, the result is that the column collapses, because the higher temperature is used to verify the stability. However, a great part of the section is under the critical temperature.

As a conclusion, according to the current steady state approach of the Eurocode, the columns should be protected with a passive fire protection in both cases. In case of the least severe fire it is demonstrated that the bare section is capable to resist the full duration of the fire, because the steady temperature is not reached, and peak temperature is lower than the critical one. In case of the most sever fire; the fire resistance is 37 minutes. If the structure has to resist the full duration of the fire, it is proposed to encase with concrete between flanges the column in the first three storeys. The insulation provided by this solution results in lower temperatures in the web and the non-exposed flange that retains structural stability.

3.8.2.3 Protected steel section

The heat fluxes curves given above in the definition of the exercise have been used as boundary conditions for heat transfer calculation, using finite element modelling. This procedure is employed here to find the thickness of the intumescent coating that has to be applied on the structure to prevent it to reach its critical temperature. Two kinds of coatings are studied here.

3.8.2.3.1 Thermal properties of intumescent coatings

The apparent thermal properties of two kind of coating have been deduced from experimental tests as described in annex 3. Using these values, several calculations can be performed to find the minimum required thickness to ensure that the steel temperature stay below the critical temperature of the considered element.

3.8.2.3.2 Heat transfer calculations

The heat fluxes given in the exercise definition are used as input for the 2D heat transfer calculation. In the present approach, the intumescent coating thickness is assumed to be ten times larger than its initial value. For each simulation, the local temperatures in the middle of the web and in the flange exposed to fire have been investigated in order to have an idea of the heating of the section. Iterative calculations have led to the estimation of the minimum thickness required.

Figure 24 gives an example of the temperature field during the heating phase. This shows the effect of the coating which acts as a thermal barrier for the external heat flux. This figure corresponds to the end of the heating phase, when the heat flux begins to decrease.

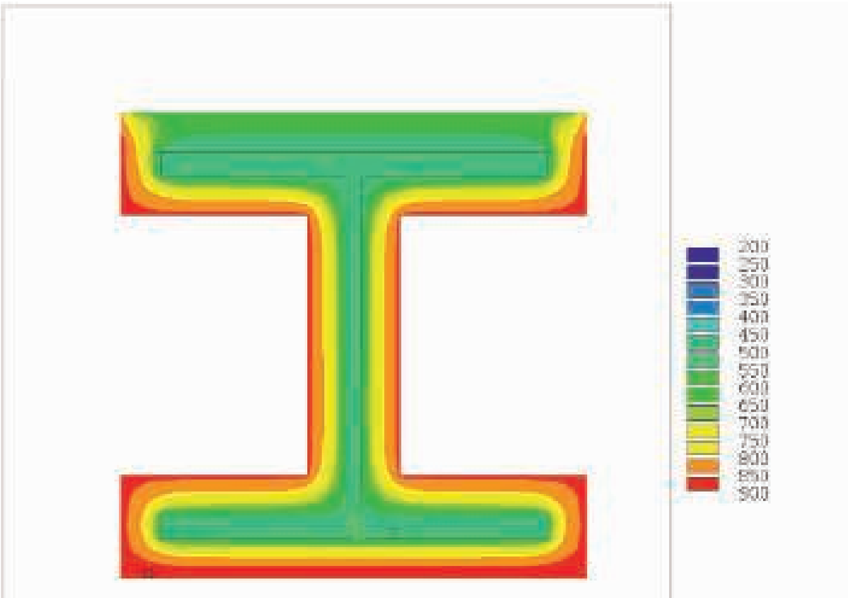


Figure 24 - Example of temperature field in the section during the heating phase (°C)

Figure 25 shows the temperature field during the cooling of the section. The thermal gradient is reversed compared to the previous figure. This figure corresponds to the time when the maximum temperature is reached by the section.

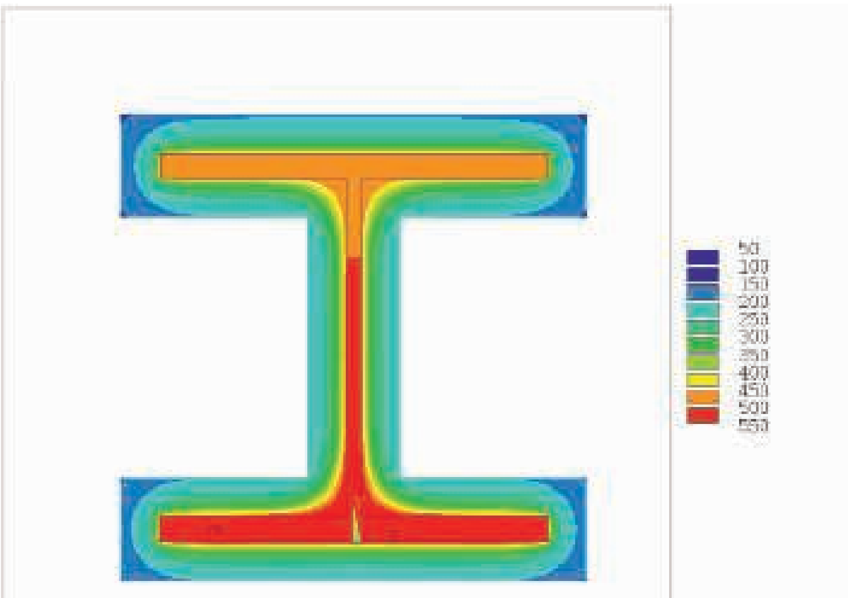


Figure 25 - Example of temperature field in the section during the cooling phase (°C)

3.8.2.3.3 Determination of the thickness of the coating

3.8.2.3.3.1 Level 1: Fire in a library

Several calculations have been performed with different values of coating thickness for this scenario with the two coatings. The maximum temperatures reached by steel are given in Figure 26 and Figure 27.

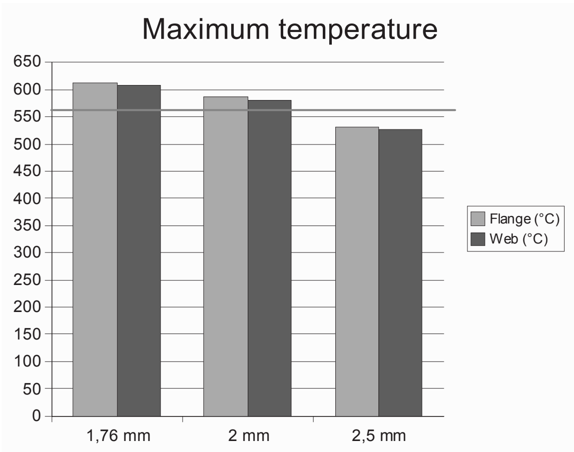


Figure 26 - Maximum temperatures reached within the section for coating 1

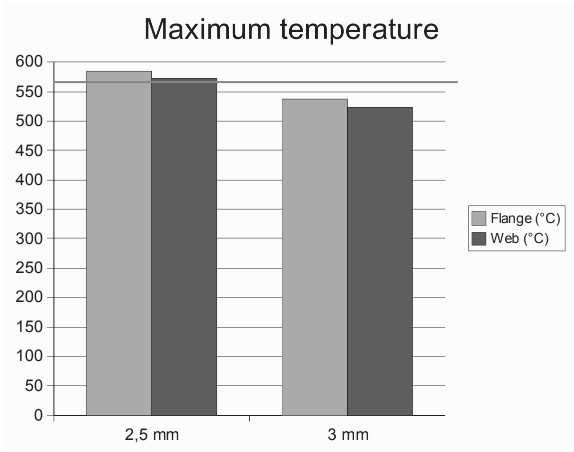


Figure 27 - Maximum temperatures reached within the section for coating 2

This study shows that a thickness of 2.5 mm for coating 1 and 3.0 mm for coating 2 is sufficient to maintain the section below its critical temperature. Figure 28 gives an example of the evolution of temperature within the section.

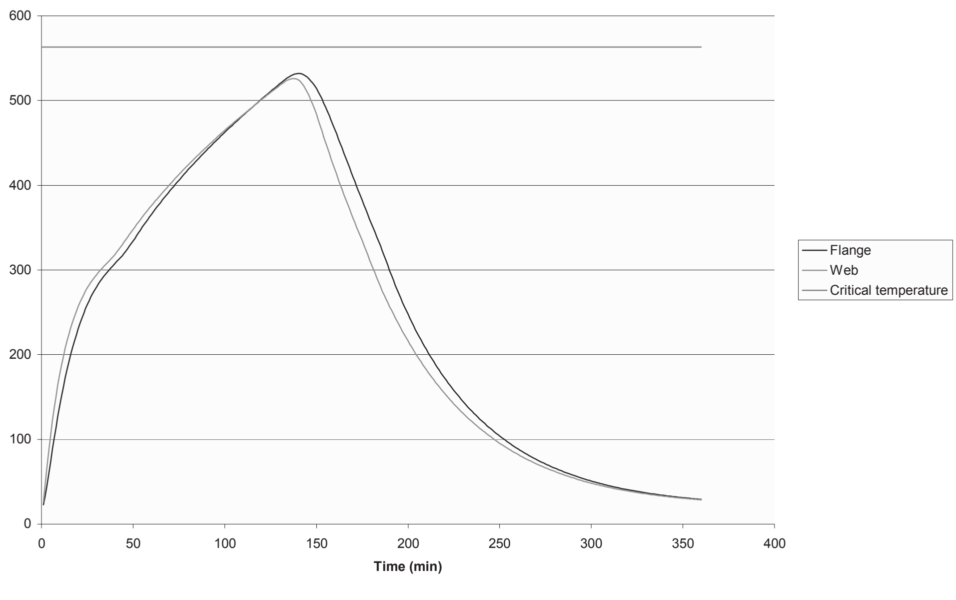


Figure 28 - Evolution of temperature during fire in a library in the section insulated with 2.5 mm of coating 1 (°C)

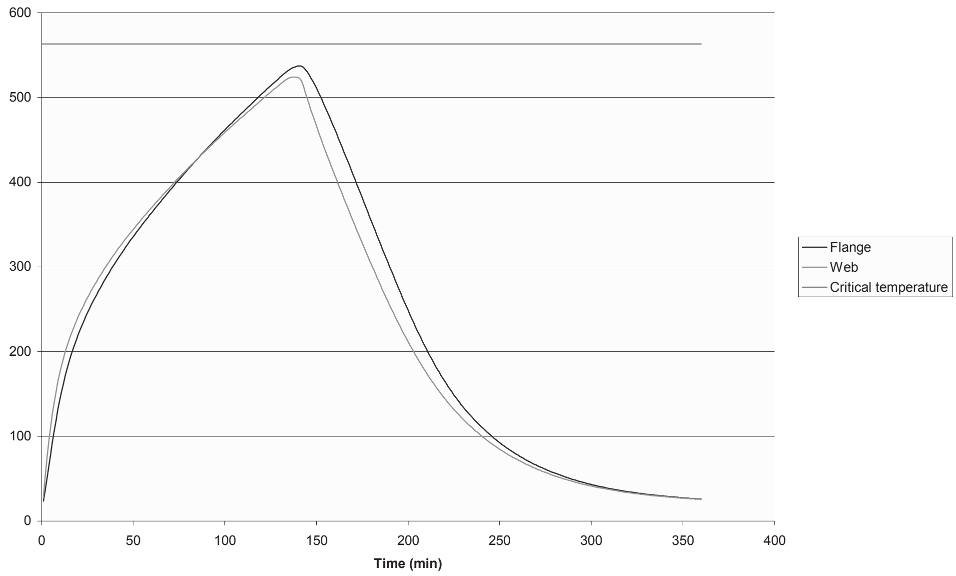


Figure 29 - Evolution of temperature during fire a library in the section insulated with 3.0 mm of coating 2 (°C)

3.8.2.3.3.2 Level 2: Fire in an office

The same procedure is done with the fire scenario at the office level. A solution proposed here is to use thickness of 0.6 mm for coating 1 and coating 2. The corresponding curves are shown in Figure 30 and Figure 31.

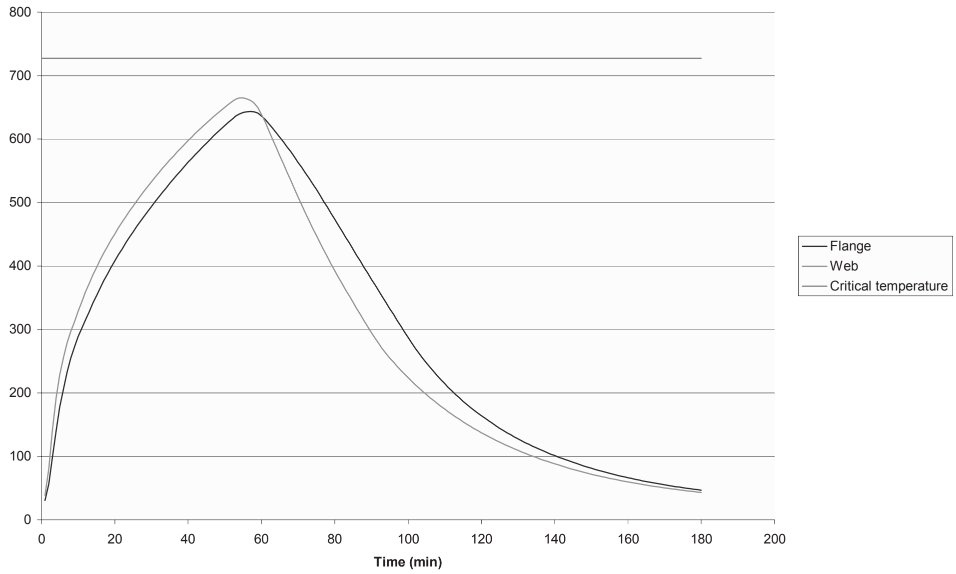


Figure 30 - Evolution of temperature during fire in an office in the section insulated with 0.6 mm of coating 1 (°C)

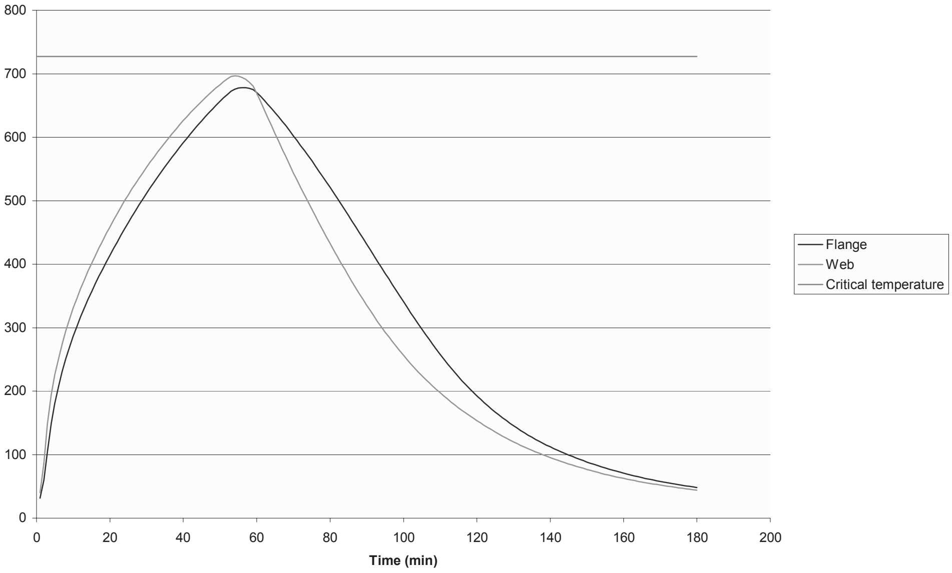


Figure 31 - Evolution of temperature during fire in an office in the section insulated with 0.6 mm of coating 2 (°C)

3.8.2.3.4 Conclusion

This study has shown an illustration of the use of equivalent thermal properties for the estimation of the required thickness of intumescent paint. Two types of coating have been used and the corresponding thicknesses are close. The scenario of a fire in a library requires a thickness which is five times larger than for the scenario of a fire in an office. This is due to the difference of the duration of the fire between the two cases. A good accuracy when estimating the thickness to be applied on members is important in order to reduce the protection cost.

3.8.2.4 Encased section

3.8.2.4.1 Heat fluxes

The maximum heat fluxes reached by the unprotected members were determined above on the basis of the Eurocode method and are given in Table 10. The heat fluxes have been transformed into flame (or gas) temperatures using the equation

$T = (\frac{\phi}{\sigma})^{1/4}$, where T is the gas temperature (K), ϕ is the heat flux (W/m^2) and σ is the Stefan-Boltzmann constant (5.67 × 10^{-8} W/m^{2}K^4)

Column side	Maximum value of heat flux	Corresponding flame (hot gas) temperature
ϕz- (exposed side)	88500 W/m^2	1117.74 K
ϕz+ (unexposed side)	34200 W/m^2	881.27 K
ϕx- (left side (when facing building))	81200 W/m^2	1093.94 K
ϕx+ (right side (when facing building))	81200 W/m^2	1093.94 K

Table 10 - Maximum values of heat fluxes and corresponding flame (hot gas) temperatures used for the calculations

The heat flux step from zero to its maximum value takes place at time t = 420 s and the step back to zero takes place at time t = 3125 s for fire load 30 kg/m2 and t = 7890 s for 100 kg/m2.

3.8.2.4.2 Results for external members

3.8.2.4.2.1 Level 2 (Office level)

The study was begun at Level 2 (Office level), where the fire load is 30 kg/m2. The problem is solved for the following types of encasements:

- 1 mm carbon steel (Mbox) encasement, air gap 12 mm
- 2 mm carbon steel (Mbox) encasement, air gap 12 mm
- 1 mm stainless steel (Sbox) encasement, air gap 12 mm
- 2 mm stainless steel (Sbox) encasement, air gap 12 mm
- 1 mm stainless steel (Sbox) encasement, air gap 30 mm
- 1 mm stainless steel (Sbox) encasement, air gap 2 mm

In the first four cases, the air gap between the column flanges and the steel encasement was 12 mm. The calculation program is based on the assumption that the air gap is relatively small so that the heat transfer between the encasement and the column can, within reasonable accuracy, be assumed to take place in four separate compartments. On the other hand, decreasing the air gap thickness will lead to lower column temperatures. However, the differences are not too great in the practical range. Emissivity values are $\varepsilon = 0.7$ and $\varepsilon = 0.5$ for carbon and stainless steels, respectively.

Figure 32 to Figure 37 give the calculated temperatures for the above 6 cases. Figure 9 shows a comparison of all maximum steel column temperatures reached during the calculations.

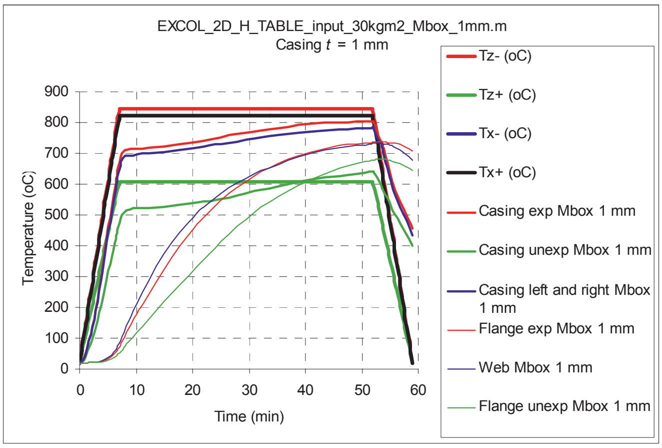


Figure 32 - Results for 1 mm carbon steel (MBox) encasement, air gap 12 mm

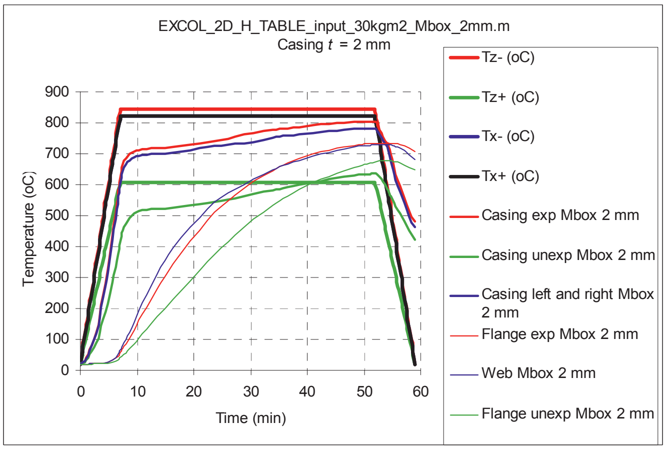


Figure 33 - Results for 2 mm carbon steel (MBox) encasement, air gap 12 mm

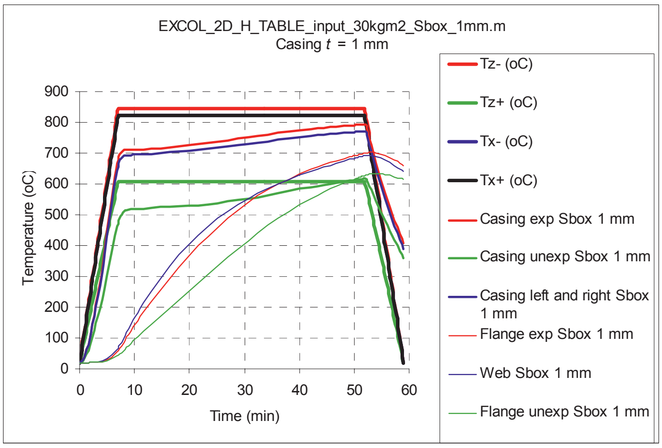


Figure 34 - Results for 1 mm stainless steel (SBox) encasement, air gap 12 mm

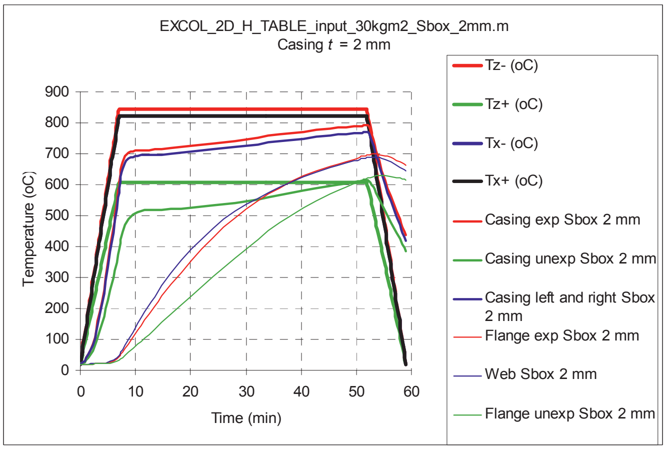


Figure 35 - Results for 2 mm stainless steel (SBox) encasement, air gap 12 mm

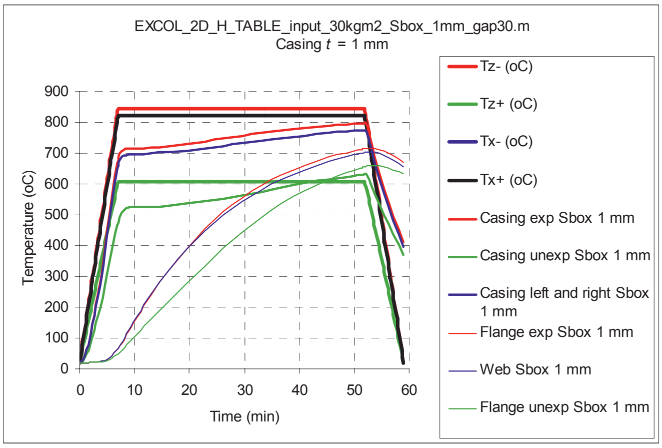


Figure 36 - Results for 1 mm stainless steel (SBox) encasement, air gap 30 mm

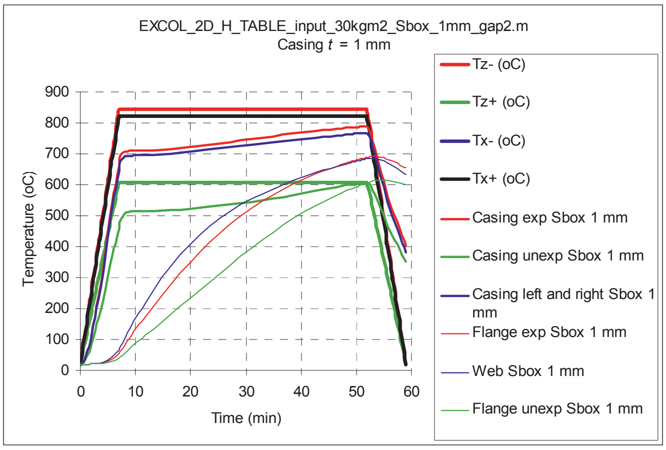


Figure 37 - Results for 1 mm stainless steel (SBox) encasement, air gap 2 mm

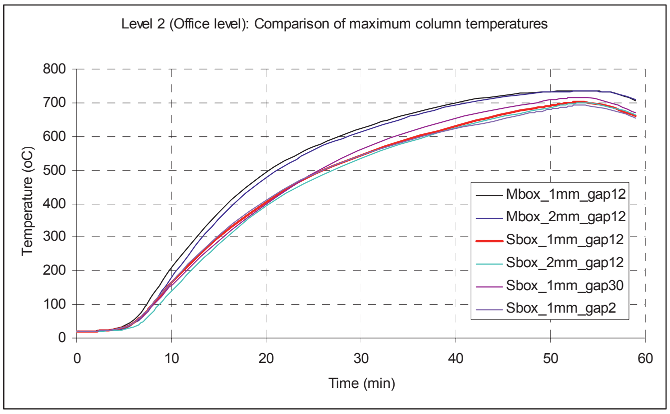


Figure 38 - Comparison of maximum column temperatures in different calculation cases at Level 2

It can be seen from Figure 38 that, using a stainless steel casing (Sbox) will reduce the column temperatures by almost 100 degrees at 30 minutes when compared to using a carbon steel casing (Mbox). This is mainly due to the differences in emissivities between stainless steel and carbon steel. However, closer to time 60 minutes, the difference has decreased. On the other hand, increasing the casing steel thickness from 1 mm to 2 mm does not appear to have much influence on the results. It should be noted, though, that the program does not calculate heat transfer through the casing wall but instead assumes that the casing temperature is uniform along its thickness, so the only difference in the calculations is the increased heat absorption capacity of the thicker casing wall. Also, the influence of air gap variation is small.

It can be seen that when the 1 mm stainless steel casing (Sbox) is used (with air gap 12 mm), the critical temperature is not reached during the fire. When using a carbon steel casing (Mbox), the critical temperature is reached approximately at time t = 47 minutes, regardless of the casing steel thickness.

3.8.2.4.2.2 Level 1 (Library level)

Based on the calculations at Level 2 (Office level), it is clear that the protection of the steel columns using a simple casing is sufficient only for fire class R30 due to the much longer fire duration and the lower critical temperature of the columns. Already in the case of Level 2 fire load (30 kg/m2), the critical temperature T = 563°C is reached at time t = 31 minutes. This is valid for Level 1 as well, because the fire exposures are similar in both cases up to time 3125 s (52 minutes).

For higher fire resistance times, additional or different type of fire protection has to be used. For instance, insulation rock wool could be installed between the casing and the column. However, this case cannot be calculated using the present program. Instead, e.g. a 2D finite element analysis should be carried out in order to evaluate the required insulation thickness.

3.8.2.4.2.3 Use of heat fluxes calculated according to LABEIN method

3.8.2.4.2.3.1 Gas temperatures

The gas temperatures on different sides of the steel column calculated on the basis of the heat fluxes provided by LABEIN for the analysis case are given in Figure 39 for Level 2 (Office level) and Figure 40 for Level 1 (Library level).

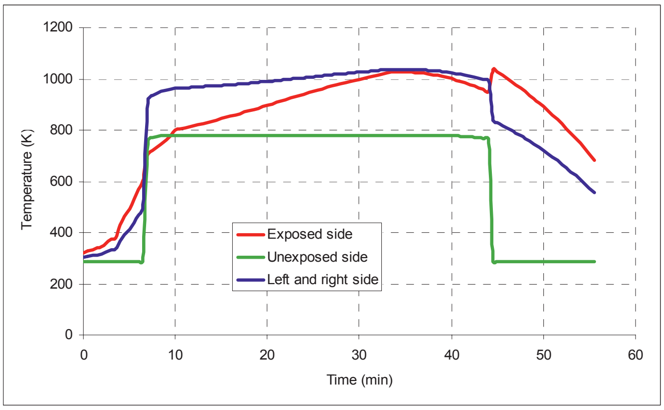


Figure 39 - Variation of gas temperatures based on LABEIN calculations for Level 2 (Office).

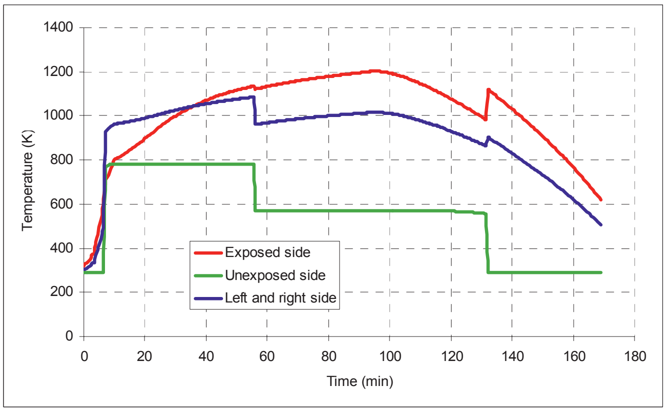


Figure 40 - Variation of gas temperatures based on LABEIN calculations for Level 1 (Library).

3.8.2.4.2.3.2 Level 2 (Office level)

The situation at Level 2 (Office level) was calculated for the steel column protected with a 1 mm thick stainless steel casing (Sbox) with a 12 mm air gap. The results are shown in Figure 41. The maximum steel column temperature is considerably lower than the critical temperature for the column at this level.

The calculation was repeated for a similar setup but with a carbon steel casing. The results are shown in Figure 42. It can be seen that the maximum steel column temperature reached during this analysis is also lower than the critical column temperature at this level.

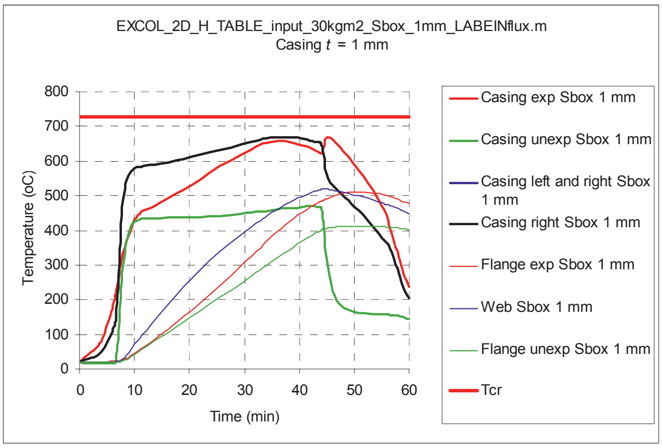


Figure 41 - Results for 1 mm stainless steel (SBox) encasement, air gap 12 mm, when gas temperatures based on LABEIN calculations (according to Figure 10) are used.

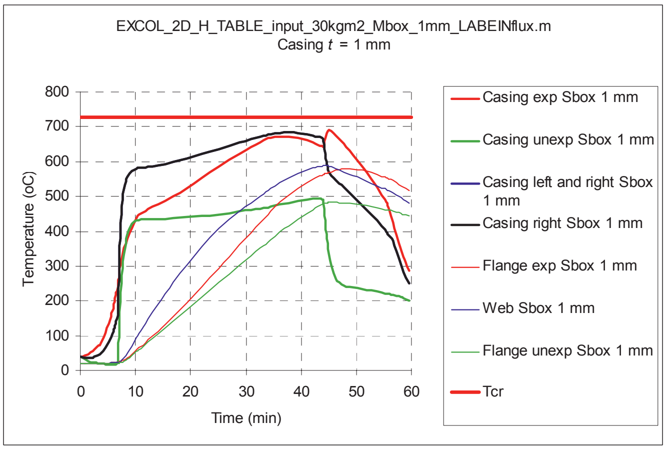


Figure 42 - Results for 1 mm carbon steel (MBox) encasement, air gap 12 mm, when gas temperatures based on LABEIN calculations (according to Figure 10) are used.

3.8.2.4.2.3.3 Level 1 (Library level)

At Level 1 (Library level), a 1 mm stainless steel casing with an air gap of 12 mm, was used. The calculated temperatures are shown in Figure 43. The critical temperature of the steel columns is reached at time t = 47 minutes according to the calculations.

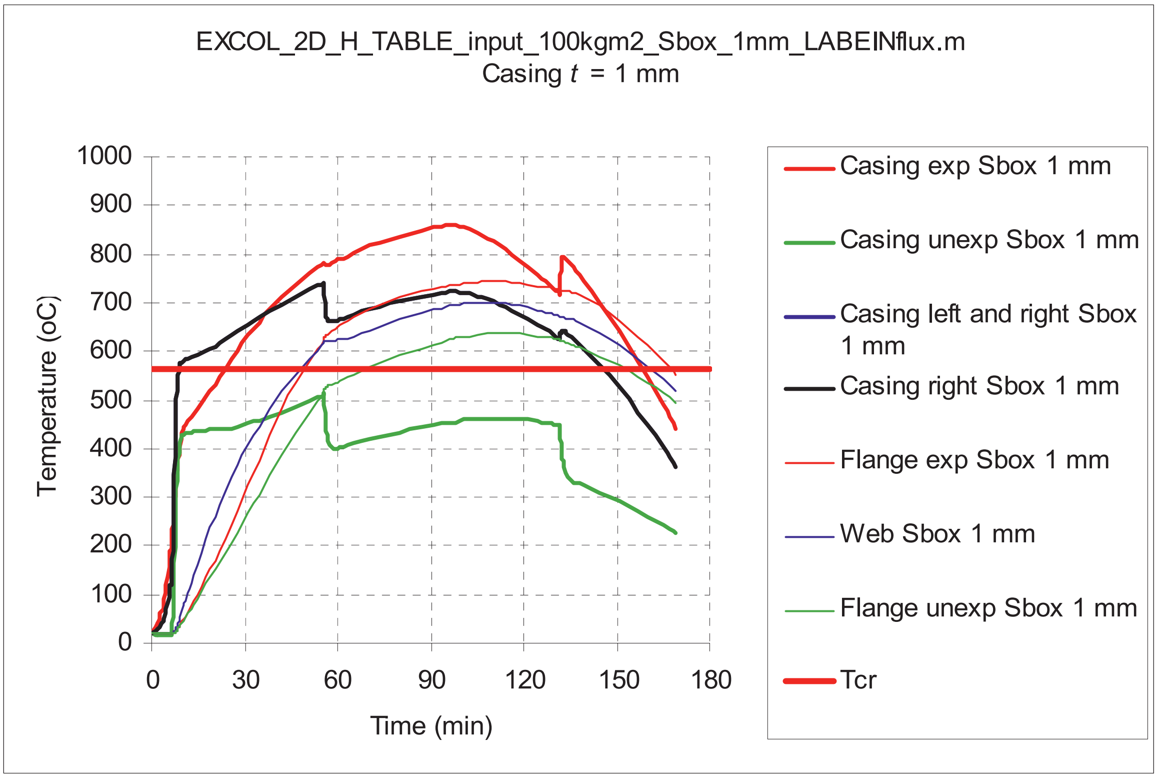


Figure 43 - Results for 1 mm stainless steel (SBox) encasement, air gap 12 mm, when gas temperatures based on LABEIN calculations (according to Figure 11) are used.

3.8.2.4.3 Conclusion

The external steel columns in the present study case were considered using two fire scenarios: according to the Eurocode method, and according to calculations based on the LABEIN fire model.

Using either one of the fire scenarios at level 2 (Office level), the external steel columns did not reach their critical temperature during the whole fire situation, when a 1 mm stainless steel casing with an air gap of 12 mm was used for fire protection of the steel column. With a 1 mm carbon steel casing and an air gap of 12 mm, the critical temperature was reached at time t = 47 minutes, when the Eurocode fire scenario was used. When the LABEIN fire model was used as basis for the gas temperatures, the maximum temperature of the steel column protected with a carbon steel casing was 589°C, which is lower than the critical temperature. Therefore the acceptability of the carbon steel casing at Level 2 (Office level) depends on the choice of fire scenario, but the stainless steel casing fulfils the requirements for both fire scenarios, according to the calculations.

At level 1 (Library level), fire protection using a simple steel casing is not sufficient for the studied fire scenarios. In order to decrease the calculated steel column temperatures, additional insulation should be used between the casing and the column.

4 CONCLUSIONS

The present report has been written after a research project of 42 months, by 5 European partners. It was based on the real need within the building community for refurbishment of buildings, but also for the design of new buildings. The project management has consisted on verifying the conformity with the technical annex of the contract, and verifying that all conclusions were made in scientific and consistent approach.

The present work has been based on numerical and experimental analysis performed within the project, but also based on the existing experimental data. It has been also based on the knowledge used for the development of the current eurocode model given in the annexes of the Eurocode 1 "actions in case of fire" part 1.2 and Eurocode 3 part 1.2 "fire behaviour of steel structures".

From all these works, development of methodologies has been made for:

- determination of thermal actions of external elements in case of fire inside the building as a function of time
- thermal response of composite sections
- thermal response of steel structures protected by intumescent coatings
- thermal response of steel structure encased by the steel box

Three levels of complexity for determining the thermal actions as function of time should be used:

- a simplified analytical method
- a simplified analytical method using zone models results:
    - for temperature-time curves inside the compartment
    - for neutral axis within the compartment leading to the determination an equivalent opening
- a global model based on CFD's to deal with complex geometry or specific protection system (as deflectors).

Many recommendations are given along the report. As a scientific and consistent approach, all the results given have been verified with testing results comparison. The present work has then to be valorised with publication and standardization documents (standards or guidelines).

5 EXPLOITATION AND IMPACT OF THE RESEARCH RESULTS

The introduction of the method of the verification of fire stability for unprotected steel sections within the ENV1991-2-2 “actions in case of fire” and ENV1993-1-2 “fire behaviour of steel structures” had a real impact for convincing fire brigade, and more generally fire authorities to use steel structures outside a building without protection when the geometry of the building, the loading factors, the localization of the structural elements allowed it.

Nevertheless, in many case, these parameters did not lead to a verification of the fire stability of the structural elements. Few solutions existed to satisfy the fire stability, and no method, other than the application of the standard ISO Fire was available.

So, on one hand, the requirements in terms of standard ISO Fire level applied to internal structures were generally applied for the external elements. From this observation, solutions were limited and expensive.

On the other hand, several building, as high rise building or at least building with several levels erected before 80ies have used external steel structures without protected. Now, fire authorities asked to verify, with current method of eurocode, their fire stability. When the results show that the structure and the geometry of the built do not fulfil the fire stability, ISO Fire rating is required.

The development of a simplified transient method for determining the thermal actions to external structural elements was thus necessary. The transient methodology developed within the present project allows extending the current eurocode method for protected steel structures.

The present work allows to verify and clarify but also to modify when necessary the current eurocode method as for example the effect of balconies.

Nevertheless, the determination of the thermal actions to external steel structures as a function of time needs to calculate the thermal response of the structural elements. In fact, in term of ISO Fire rating requirements, the level of protection of steel structures are given by graphs formulating the thickness of protection as a function of the massivity factor of the section and ISO Fire rating. This approach could not be applied for heat flux as a function of time. Moreover, lot of solution used for internal elements are not possible for external elements, as for example sprays, rockwool or plasterboard encasement.

So methods to determine the thermal response of different solutions of protection or design of external structural elements have been developed in the project.

Three main solutions are available for structural elements for which the fire stability is not verified by the current eurocode model. These approaches can be used for refurbishment, but also may reduce the cost of construction. These are for instance:

- composite columns, that contrary the ISO Fire Rating, can often be verified with rebars in, but only filled of concrete
- Encasement solutions for beams and columns that generally can not fulfilled ISO Fire rating higher than 30 minutes
- Intumescent coating for beams and columns with adapted thickness: solutions that are appreciated in case of refurbishment keeping the initial architectural design

Also, the methodology allows different level of complexity: it gives some recommendations for the third level using CFD’s. This third level may also be necessary for refurbishment or specific designs when the 3 solutions given here above can not be used. For example, the use of simple steel deflector protecting the unprotected steel sections needs to verify the conditions external flaming deviation by the deflector.

For global view, the work performed within the research project will help the designers and the fire engineers to find solutions for verifying the fire stability of the external steel or composite structure.

In order to valorise the present work, the methodology developed within the project should be introduce in standardization, either in European standardization as next versions of Eurocodes, or in International Standardization as ISO/TC92/SC4 Fire Safety Engineering.

In the future, articles will be published or presented in national, European or international conferences for valorisation by the different partners.

6 LIST OF FIGURES AND TABLES

6.1 Figures

6.2 Tables

7 LIST OF REFERENCES

Reference	Title	Institute	Author
PR380-N. 01	Contract ECSC		
PR380-N. 02	Agenda 1st meeting Paris - 20th September 2002	CTICM	D. Joyeux
PR380-N.03	Thermal exposure to a high welded I-beam above pool fire	VTT	J. Myllymaki
PR380-N.04	Minutes of 1st meeting Paris - 20th September 2002	CTICM	D. Joyeux
PR380-N. 05	Températures en façade / Résultats expérimentaux d'incendies naturels - rapport CTICM N° 1-012-6 - octobre 1980	CTICM	I. Ryan J. Kruppa
PR380-N. 06	Etude expérimentale de la transmission du feu par les façades au voisinage d'un angle rentrant Rapport CTICM N° 1-012-1 - décembre 1978	CTICM	J. Kruppa
PR380-N. 07	Aerothermodynamics of fully involved enclosure fires having external flames		M. Delichatsios
PR380-N. 08	Part II - Description of proposed research concerning flames in facade		M. Delichatsios
PR380-N. 09	Fully involved enclosure fires: effects of fuel type, fuel area and geometry		M. Delichatsios
PR380-N. 10	Draft Agenda 2nd meeting Paris - 16th January 2003	CTICM	D. Joyeux
PR380-N. 11	Annual report 2001 - Contract 7210-PR-184 - Version March 2002	BRE	
PR380-N. 12	Semestrial report 2001 - Contract 7210-PR-184 - Version Sept. 2001	BRE	
PR380-N. 13	Semestrial report 2002 - Contract 7210-PR-184 - Version Sept. 2002	BRE	
PR380-N. 14	Temperature calculation of sheet steel protected sections - the radiation heat transfer in the void - WP 4	VTT	J. Myllymaki
PR380-N. 15	Natural fire experiments on the lightweight steel balconies	VTT	J. Myllymaki
PR380-N. 16	Minutes of 2nd meeting Paris - 16th January 2003	CTICM	D. Joyeux
PR380-N. 17	Annual report 2002 - B37	CTICM	D. Joyeux
PR380-N. 18	CTICM - Validation case for CFD tests	CTICM	S. Desanghere
PR380-N. 19	CTICM - Validation case updated	CTICM	S. Desanghere
PR380-N. 20	Experimental and Numerical Assessment of the Behaviour of External Heavy Steel Columns Under Natural Fire	CTICM	D.Dhima G.Fouquet D. Joyeux J.Kruppa B.Zhao
PR380-N. 21	Agenda 3rd meeting Bilbao - 28th June 2002	CTICM	D. Joyeux
PR380-N. 22	Presentation F6 27 mai 2003 Daniel Joyeux	CTICM	D. Joyeux
PR380-N. 23	WP4: Test programme to be carried out at VTT	VTT	OK
PR380-N. 24	Simulation of the Fire Test for External Steel Structures VTT	VTT	SH
PR380-N. 25	Validation case updated - VTT	VTT	SH

PR380-N. 26	Minutes of 3rd meeting Bilbao - 18th June 2003	CTICM	D. Joyeux
PR380-N. 27	ProfilArbed - Backgroung document on advanced fire models according to 3.3.2 of prEN1991-1-2 (24-08-2001)	ProfilArbed	M. Haller
PR380-N. 28	LABEIN : Semestrial report September 2003	LABEIN	J. Unanua
PR380-N. 29	ProfilArbed : PARE contribution to the semestrial report	ProfilArbed	M. Haller
PR380-N. 30	Semestrial report Period 01 January - 30 June 2003	CTICM	D. Joyeux
PR380-N. 31	Progress report WP1 : Projection of external flames by openings	TNO	T. Lemaire
PR380-N. 32	AGENDA : 4th meeting - 17th October 2003	CTICM	D. Joyeux
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PR380-N. 38	ACTIONS FOR THE BENCHMARK	CTICM	S. Desanghere
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PR380-N. 40	Compte-rendu d'essai 76 R5 / T1 - Essai de réchauffement d'un assemblage métallique protégé, soumis à un feu naturel	CTICM	D.Joyeux
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PR380-N. 55	Minutes of the 6th meeting held on June 2004 in Espoo	CTICM	S. Desanghere
PR380-N. 55a	Meeting Espoo June 2004 – Presentation TNO 1	TNO	AD Lemaire
PR380-N. 55b	Meeting Espoo June 2004 – Presentation TNO 2	TNO	
PR380-N. 55c	Meeting Espoo June 2004 – Presentation TNO 3	TNO	
PR380-N. 55d	Meeting Espoo June 2004 – Presentation TNO 4	TNO	
PR380-N. 55e	Meeting Espoo June 2004 – Presentation TNO 5	TNO	
PR380-N. 55f	Meeting Espoo June 2004 – Presentation LABEIN	LABEIN	
PR380-N. 55g	Meeting Espoo June 2004 – Presentation PROFILARBED	ProfilArbed	
PR380-N. 55h	Meeting Espoo June 2004 – Presentation PROFILARBED 2	ProfilArbed	
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PR380-N. 59	Synthesis of Fire test 02E053	CTICM	A. Blanguernon
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PR380-N. 72	Minutes of the 7th meeting held on October 2004 at Maizières	CTICM	D. Joyeux
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8 TECHNICAL ANNEX

Contract N° : 7210-PA/PB/PC/PD/PE/380

Reference N° : 02-F6.04a',b,c,d,e

Project n°: P4556

DEVELOPMENT OF DESIGN RULES FOR THE FIRE BEHAVIOUR OF EXTERNAL STEEL STRUCTURES

OBJECTIVES

The aims of this research are the following:

- To improve the existing model for determining the thermal actions on external bare, insulated or shielded structural elements, taking into account radiative and convective heating by external flames and by the opening of the compartment in fire itself.
- To extend the existing physical model for temperature development within structural elements (steel or composite) by including transient state conditions and, when necessary, the effects of fire protection systems such as fire insulation and thermal shielding, taking into account heat transfer across air gaps.
- To verify the developed models on the basis of experimental results and to adapt the models, where appropriate.
- To develop simple rules on the heating of bare or protected external steel sections, steel section away from a localised fire and balconies, in case of fire.

WORK PROGRAMME AND DISTRIBUTION OF TASKS

General

The work is divided in 6 work packages, one of which is concentrating on the thermal actions under natural fire conditions. Others concentrate on the temperature response of specific types of structural elements, fire protection conditions and thermal exposure conditions to such thermal actions. Within each of these Work Packages the three kinds of work described below will be considered.

- Work on the adjustment and – where necessary the development - of theoretical models. This work takes into account existing knowledge available in literature (see, for instance, some references below), and will be extended by applying analytical and numerical tools available within the consortium.
- Experimental verification of the theoretical prediction models by carrying out (or using existing) fire tests to obtain the necessary additional knowledge to check the improved calculation methods and/or to investigate specific thermal behaviours.
- Development of simple calculation rules to be, further, incorporated in Structural Eurocodes.

A special Work Package is devoted to co-ordination activities.

Work content

The 6 work packages (WP) are covering the various areas needed in the whole development work and management. The detailed contents of work packages (including estimated costs) are presented in the following tables.

WP 1 - Projection of external flames by openings

Responsible partner: TNO	Other partners: CTICM, LABEIN, VTT
Objectives: Development of methods to predict the heat flux to structural elements from external plumes	
Description: The tasks are: Introduction of literature data on external and façade fires gathered since the development of the present model by M. Law in the seventies. Emphasis is on : - Application of recent developments in natural compartment fire analysis to predict the source of thermal radiation by openings. - Development of a numerical “scanning technique” to predict radiative heat flux to structural elements more accurately than in the present models. - Application of Computational Fluid Dynamics modelling techniques to predict geometry, temperature and composition of flames projecting from openings, with or without balconies and to predict convective and radiative heat transfer to structural elements within or adjacent to the flames. The theoretical model will be verified by carrying out a limited number of well-conditioned experiments in conjunction with similar work within the other work packages. These experiments will provide also data on steel sections, unprotected and protected by shielding. The work will be completed by sensitivity analysis to ensure reliability of the models on the given ranges and the development of simple calculation rules for thermal exposure and heat transfer characteristics on structural elements for inclusion in the Structural Eurocodes.	
Activity: Theoretical work Experimental testing	

WP 2 - Heating up of steel or composite bare sections

Responsible partner: LABEIN	**Other partners: ARBED, CTICM, TNO**
Objectives: Development of temperature calculation methods for composite external elements	
Description: For bare steel the existing simplified model to calculate the steel temperature described in ENV 1993-1-2 will be updated to take into account transient radiative and convective heat flux produced by external flame or by localised fires. The view factor governing the radiative heat exchange will be investigated in details because its influence is relevant in the heating of external elements made with mild or stainless steel. For composite sections, numerous numerical analyses calculating the temperature field in composite elements, when exposed to natural fires, will be performed in order to deduce simplified models to be incorporated in Structural Eurocodes. Results of tests performed within other work packages will be taken into consideration for checking the accuracy of the simplified calculation methods developed.	
Activity: Theoretical work	

WP 3 - Heating up of protected steel sections

<table>
<tr><td>Responsible partner: CTICM</td><td>Other partners: ARBED, VTT</td></tr>
<tr><td colspan="2">Objectives: Development of temperature calculation methods for protected external elements</td></tr>
<tr><td colspan="2">Description:

Based on the improved calculation methods developed within WP 2, further developments will be performed in order to cover the case of sections insulated by protection materials as intumescent paints. Additionally, a proposal will be made to obtain the necessary thermal characteristics of protection materials to be used under natural fire conditions. The following steps will be carried out :

- assessment by numerical simulations of the heating up of external steel section insulated by a protection material;

- experiments, on a limited number of cases, under natural fire conditions, to obtain the necessary data to check the accuracy of the numerical simulations for insulated steel and composite external elements, as well as to provide data for WP1 (temperatures for external flames) and WP 2 (temperatures of bare steel and composite elements);</td></tr>
<tr><td colspan="2">Activity:

Theoretical work

Experimental testing</td></tr>
</table>

WP 4 - Heating up of external steel sections protected with steel box and of balconies

<table>
<tr><td>Responsible partner: VTT</td><td>Other partners: CTICM, LABEIN</td></tr>
<tr><td colspan="2">Objectives: Development of temperature calculation methods for external steel structural elements and balconies shielded by steel or stainless steel</td></tr>
<tr><td colspan="2">Description:

The tasks are:

Application of mild steel or stainless steel box shielding could be sufficient for the protection of structural members in several cases. Profiled steel sheets can be used as a load bearing members and also as a shielding to the structural members of external balconies. A method to assess the thermal properties, emissivity and convection factors, of steel encasements will be developed. The following studies will be conducted:

- experiments on the behaviour of steel members protected with mild steel or stainless steel encasement in a case of an external fire

- experiments on the heating up of balcony structures with protected balcony slabs and unprotected columns and exposed to the flames emerging from the window opening, providing also information for WP1 and WP2 about effect of awnings to the fire plumes.

- numerical simulations of the heating up of steel sections protected with steel box

- numerical computations of temperature of balcony slabs and columns

- sensitivity analysis to ensure reliability of the models on the given ranges

- development of a simple calculation method for box or shield encasements, to be incorporated in Structural Eurocodes.

- development of a simple temperature calculation method for balcony slab structures made of layered profiled steel sheets, to be incorporated in Structural Eurocodes</td></tr>
<tr><td colspan="2">Activity:

Theoretical work

Experimental work

Design work</td></tr>
</table>

WP 5 - Heating up of sections by localised fires

Responsible partner: ProfilARBED	**Other partners: TNO**
Objectives: Development of temperature calculation methods for internal steel structural elements exposed localised fires	
Description: The tasks are: Based on fire engineering methodology, simple tools will be developed to determine the temperature of an unprotected steel section submitted to unconfined (localised) fires, with no accumulation of smoke. The work on the view factor, governing the radiative heat exchange, to be made within WP 2, will be taken into consideration within this WP 5. The following studies will be conducted: - research of experimental data on the temperature of steel members located in the vicinity of localised fires - numerical simulations of the heating up of these steel sections - sensitivity analysis to ensure reliability of the model on the given ranges - development of a simple temperature calculation method for these elements, to be incorporated in Structural Eurocodes	
Activity: Theoretical work Design work	

WP 6 - Project coordination.

Responsible partner: CTICM	**Other partners: Coordinators of sub-work packages**
Objectives: **CTICM will be responsible for the overall management of the project. It will be responsible for preparing a detailed project plan indicating the key dates. It will organise 2 or 3 meetings a year among the partners and co-ordinate the semestrial and annual reports to the Commission.**	
Description: This work package covers all management and co-ordination activities required to keep the project on schedule and to cost. This includes: - Planning of work packages and their inter-relationships; - Liaison with partners and sub-contractors to monitor progress and identify difficulties; - Adoption of measures to rectify any problems; **- Progress reporting;** - Organization and running of progress meetings; - Liaison with ECSC; - Project administration	
Activity Project management Final report	

European Commission

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