Scientific background to the harmonization of structural Eurocodes

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Structural Eurocodes are a set of 58 different parts dealing with all the aspects of the design of buildings and civil works. Among them are some parts devoted to the structural fire design. This paper gives some background information from various research projects which were carried out during the last decade to improve or fill some gaps in the knowledge to be able to understand the entire structural behaviour of a building when submitted to a real fire. Focus is made on the so called 'natural fire safety concept' and on projects dealing with composite (steel + concrete) structures, as well as steel members.

Key words: Structural Eurocodes, fire design, natural fire, fire safety engineering, heat transfer, mechanical behaviour, modelling

1 Introduction

The Eurocodes are a series of European standards which provide a common series of methods for calculating the mechanical strength of elements playing a structural role in construction works (hereinafter 'structural construction products'). Those methods make it possible to design construction works, to check the stability of construction works or parts thereof and to give the necessary dimensions of structural construction products [1].

The Eurocodes provide common design methods, expressed in a set of European standards, which are intended to be used as reference documents for Member States to [2]:

- prove the compliance of building and civil engineering works or parts thereof with Essential Requirement n°1 *Mechanical resistance and stability* (including aspects of Essential Requirement n°4 *Safety in use*, which relate to mechanical resistance and stability) and a part of Essential Requirement n°2 Safety in *case of fire*, including durability, as defined in Annex 1 of the Construction Product Directive

- express in technical terms these Essential Requirements applicable to the works and parts thereof
- determine the performance of structural components and kits with regard to mechanical resistance and stability and resistance to fire, insofar as it is part of the information accompanying CE marking (e.g. declared values).

In the end of 2004, the 58 different parts which formed the Eurocode set are all nearly reaching the stage of EN (European Norm) and will be implemented, as wished by the European Commission and the Members States, within some years throughout the European Union, the Economic European Area and, also, in a lot of other countries. Among these parts, 7 dealt with 'structural fire design'.

As far as these 'fire parts' of Eurocodes are concerned, to reach this stage, a huge amount of work, involving many European research institutes and experts, was needed. Generally based on existing recommendations developed, for instance, by European Commission for Constructional Steelworks (ECCS), Fédération Européenne du Béton (FEB), Fédération International de la Précontrainte (FIP)… the European Commission have set a group of 13 experts [3] in 1988 to write the first drafts of Eurocode fire parts.

In mid-1990 a series of parts dealing with actions on structures exposed to fire and with fire resistance design of structures made in concrete, steel, composite and timber were officially presented in a seminar on 25 to 27 June 1990 in Luxemburg to the potential users.

At this time, the European Commission took the decision to forward the further development of these Structural Eurocodes to the Comité Européen de Normalisation (CEN) and in 1993-1995, new versions of these fire parts were issued, under the reference ENV 1991-2.2 to ENV 1999-1.2 [4, 5].

These 'pre-standards' were used in some European countries and decision was taken, at the end of the 90's to convert them to 'full European standards', leading now to the series of EN1992-1.2 to EN 1999-1.2.

To illustrate the progress made in each version, table 1 presents the content of the annexes of the various versions of Eurocode 1 on actions in case of fire, from 1990 to 2002.

The current final version of the Eurocode fire parts are given a wide range of tools for designing entire structures or parts thereof for any kind of fire scenario. These tools can be very simple when based on tabulated data, user friendly when based on analytical formulae or very efficient when based on advanced calculation method such as the finite element method at elevated temperatures.

Table 1. Comparison of the content of annexes of Eurocode 1- 1.2

Item	**"Chapter 20" – 1990**	**"ENV 1991-2.2" - 1995**	**"EN 1991-1.2" – 2002**
Fire load density	5 pages in annexes 0 and 3	5 pages – annex D	7 pages – annex E
Fire modelling	4 pages in annexes 1 and 2	None	2 pages – annex D
Parametric fires	None	3 pages – annexes A and B	3 pages – annex A
Equivalent time of fire exposure	1 page – annex 5	2 pages – annex E	2 pages – annex F
Thermal actions for external members	6 pages – annex 6	8 pages – annex C	9 pages – annex B
Localised fires	none	none	3 pages – annex C

Hereafter, some examples are given of research projects carried out, showing the output they have provided. They dealt with:

a. Natural fire safety concept to provide in-depth background information for assessment of the behaviour of either large structural volume or car park structures when submitted to real fire development
b. Fire design of steel structures either made with stainless steel or lightweight structural elements
c. Fire design of composite structures either for beams or slabs.

2 Natural Fire Modelling

When dealing with realistic fire scenarios, the fire safety design is based on physically determined thermal actions. In contrast with conventional fire design, parameters like the amount of fire load, the rate of heat release and the ventilation factor play an important role in the fire design. The specification of appropriate and realistic design fire scenarios is a crucial aspect of fire safety design. The assumptions made with regard to these factors have a major influence on the thermal conditions within a compartment and have a significant impact on the fire design. The design fire scenarios used for the analysis/development of a building fire have to be deduced from all the possible fire scenarios. In most buildings, the number of possible fire scenarios is infinite and need to be reduced. Only 'credible worst case fire scenarios' will be studied. If the design fire scenarios are chosen, a number of fire models are available to calculate the thermal actions.

Different characteristics relevant for the assessment of design fires are listed by a working group led by Leen Twilt et al [27]. Regarding the methods for assessing the fire severity, different levels of fire calculation methods are relevant to the various stages of fire development. When a fire is initiated, it is localised within a compartment and, according to the characteristics of the compartment and of the fire load, it can remain localised or becomes generalised to the whole compartment.

In many cases of small compartments or small opening regarding the compartment size, the fire develops into to a fuly developed fire.

Mainly three levels of modelling are available for each situation, as shown in table 2.

Table 2. Different levels of fire models

Levels of the model	**Localised fire**	**Generalised fire**
Simplified	Hasemi model Heskestad model	Parametrical fires
Zone models	2-zone model	1-zone model
Filed model	CFD	CFD

The simplified models are generally empirical models. The zone-models take into account all the main parameters controlling the fire, but introduce simplified assumptions that limit the domain of application.

The field models are rather complex for being used as a general design tool and should be limited to specific cases. Field models are the only tools valid for a complex geometry. The last European Community of Steel and Coal research projects were focussing on the improvement or the development of empirical and numerical tools [15, 17, 22].

When the conditions of flashover or generalised fire are not reached, a fire remains localised. In this condition, a two-zone model is used to estimate the general effect of the smoke layer. The local effect near the fire is also studied by empirical models developed in a previous research ‘natural fire in large compartments’ [13]. Hasemi [18, 19, 20, 21] performed experimental investigations to determine the localised thermal actions from a fire, from which a simplified method was developed. The combination of both models allows for the determination of the temperature field near and far away from the fire. The main results of the models are the thermal actions to the structure.

2.1 *Hasemi model*

In a research project devoted to large compartments [17], a calculation method was developed to estimate the temperature field and the temperature of structural elements in case of a localised fire. This method combines:

- Hasemi's model for localised fire [18], and
- Two-zone model

These two models have been implemented within the software Ozone within a European research project [15].

The validation of this calculation model has been made for both large compartments [17] and car parks [22, 23]. Because Hasemi's model was originally developed for small scale test results with rates of heat release less than 1 MW, additional validations were performed for larger fires, from 2 MW to 60 MW. For example the figure 1 shows a comparison between calculated and measured temperatures of an IPE 600 beam above a car fire, showing a relatively good agreement.

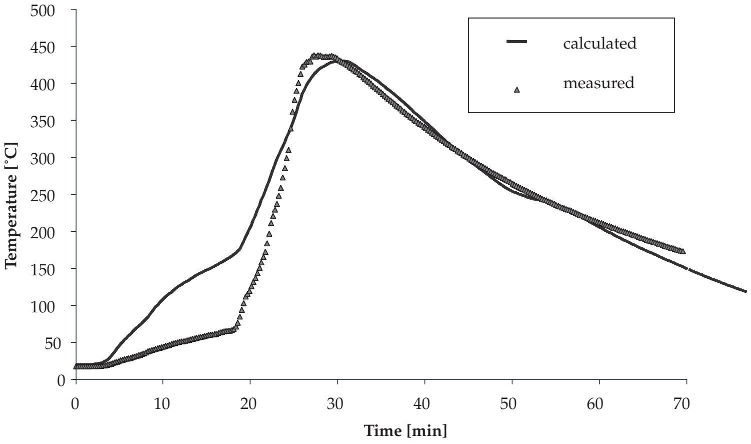


Figure 1. Comparison between calculated and measured temperatures of a steel beam above a localised car fire

2.2 *Heskestad model*

When the flames are not impacting the ceiling, an empirical method has been developed to determine the thermo-dynamic data of an open fire [6]. These empirical equations are the basis of the equations (C1) to (C3) of the revised final draft of Eurocode 1 part 1.2 (EN 1991-1.2 : 2002). The first correlation obtained from axially symmetric open fire dealt with the flame height, which is representative of the height along the axis of the flame where the average temperature is 520°C. The second empirical non dimensional correlation is given for the temperature along the axis of the plume.

The application is not considered for low flame height to diameter ratio, where a single plume does not exist. A limit of 0.5 for this ratio may be used.

Historically, these empirical equations have been developed from small scale test results. Firstly, the determination of centreline temperature equation was determined to model the plume, i.e. above the height of the flame. Further, several research works on small scale tests (less than 1000 kW) [6, 7, 8 ,9 ,10] have been carried out to verify the previous equation but also to extend their results to the flaming region. These researches have led to very similar equations with similar values of the coefficients validated on the flaming regions. In addition, these experiments have shown that the mean temperature along the axis of a turbulent open fire is never higher than 900°C.

Then, European research projects have validated the equations for large fires. Large scale test results have been used [14]. In figure 2 comparisons are made between measured and calculated temperatures along the axis for a 20 MW fire performed in 1998 in a large industrial hall [14, 22], and in one of the largest experimental test with temperature measurements with a 60MW fire performed in 1994 in an 28m high exhibition hall [11, 13].

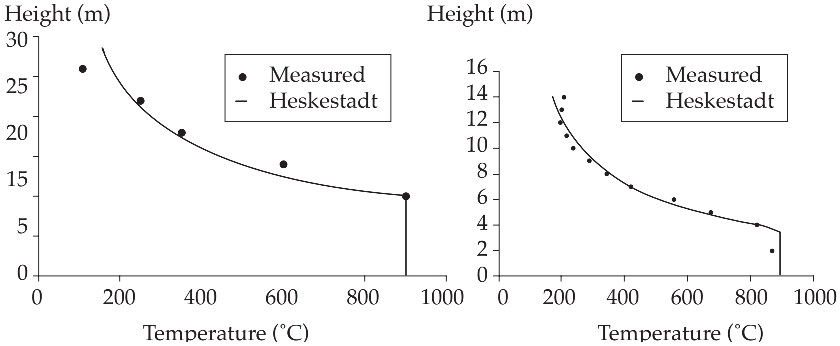


Figure 2. Comparisons between centreline calculated and measured temperatures for a 60MW fire (left) and a 20MW fire (right)

2.3 *Parametrical fires*

The parametric fires are relevant to the determination of temperature within a compartment in case of generalized fire. However, even if it is a strong improvement compared to the standard "ISO-fire", these parametric fires, as shown in the following figures, are not yet able to provide a very accurate answer of the fire severity, consequently it is recommended to use them only for pre-design calculation. These parametrical fires presented in the ENV1991-2-2 have been improved to include the multi-layer wall effect since they took into account only single layer wall, limiting the application domain; the improved version has been implemented in the EN1991-1-2 [28].

The second main improvement made for parametrical fires is the introduction of the fuel control condition, by using minimum fire duration, generally assumed as 20 minutes. This fuel control condition leads to a minimum value of O, the ventilation factor, calculated from the 20 minutes fire duration. This allows withdrawing the case of high speed fire leading to unsafe temperature.

The following figure shows the improvement for a fuel control fire, of a hotel fire test [40].

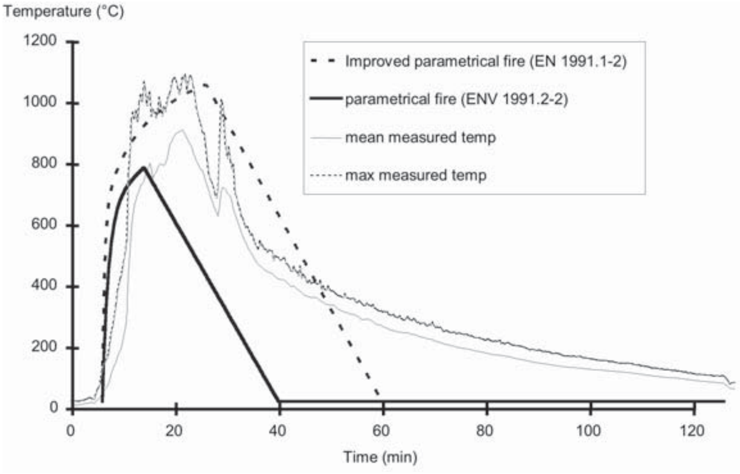


Figure 3. Effect of the improvement of the parametrical fires: comparison with experimental results of a hotel fire test

2.4 ***Zone models***

Two types of zone models exist:

- 1-zone model assuming a generalized fire
- 2 zone model assuming 2 layers: a hot upper zone and a cold lower zone.

A large number of zone-models exists in the world, the background of these models or the code source are often not available [24, 25]. A zone model, OZONE, has been developed within an ECSC research project [15]; it allows jumping from a two-zone model leading to a one-zone model when hot gas layer reaches some specific conditions (of temperature and/or height). This zone model was then validated by comparison with another existing one-zone model (NAT [16]) and with more than 100 experimental tests.

Large scale fire tests have been performed and are used for validation. The figure 4 shows, as example, the temperature-time curve comparison between tests and zone model.

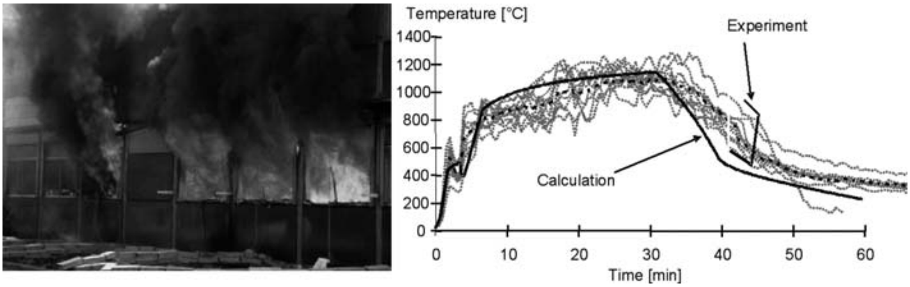


Figure 4. Comparison between calculated and measured temperatures of generalized fire in a school room

2.5 ***Characteristics of the fire compartment***

2.5.1 Boundary elements of the compartment

One of the assumptions generally made is that the fire in one compartment will not spread to other compartments. Whether this is true, depends on the fire behaviour of the boundary constructions (floors, walls [including doors], etc.). Consequently, it is necessary to understand this behaviour in order to assess their capability to act as fire barriers.
To carry out such assessment, the following options could be used:

- Calculations

  Concerning some rather simple situations, it is possible to perform heat transfer and mechanical behaviour calculations for the relevant time-temperature curve to be developed within the compartment. Such an approach need to be, preliminary, correlated with some existing test results on the same kind of separating element; however these test results mainly refer to standard fire conditions, which not allows to a wide spread of knowledge as far as the influence of the severity of fire on the behaviour of separating elements is concerned. It is why this approach needs to be linked with “expert judgments”.

- Ad-hoc tests

  The separating element can be exposed, in a furnace, to a temperature-time curve resulting from a calculation with a fire model taken into account the parameters related to a worst-case fire scenario. However the number of fire tests needed may be very large.

- Expert judgement

  This approach makes use of the available test-data of ISO-resistance tests on separating elements. In combination with calculation procedures, the behaviour under natural fire conditions can be assessed by identifying the influence of the main parameters which could lead to more onerous situations.

- Direct use of ISO-requirements

National rules define fire compartments with ISO ratings for fire resistance of walls, ceilings, doors and floors, depending on the use and the geometry of the building. Since this kinds of requirements mean implicitly that a fire will not grow beyond the fire compartment, it could be assumed that any separating element fulfilling these ISO requirements will be able to maintain the fire within the compartment for any other fire scenarios.

2.5.2 Thermal characteristics

The heat loss by convection, radiation and conduction from the compartment is an important factor for the temperature determination. Through the separating element, according to the thermal inertia of the wall (insulated or not), this heat loss is within the range of 30 % to 90% of the total amount of heat released within the compartment by the combustion of fire load, and consequently the thermal properties of the walls have to be known.

The three main parameters characterising the thermal properties of a material are:

- heat capacity c_p
- density ρ
- conductivity λ

The conductivity and the heat capacity depend on temperature. It is suggested to neglect the effect of water content since this will generally be on the safe side.

The table 3 gives the thermal characteristics of some materials, other than those already covered by Eurocodes, usually used in building.

3 Fire behaviour of steel structures

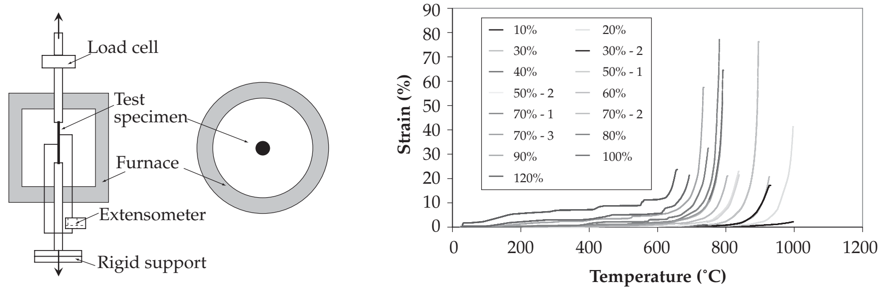
For more than three decades, there was an enormous financial effort by the steel industry to investigate the "weakness" of constructional steel structures subjected to fire and a number of design rules have been developed in this field which were incorporated within Structural Eurocodes. With respect to this situation, the recent research works have been orientated towards other types of steel structures such as stainless steel structures as well as steel and concrete composite structures. In addition, as far as local instability, for instance, the local buckling of thin wall element, is concerned, very few works were performed before 90's. Consequently two research projects have been carried out on stainless steel [29, 30], in which the fire behaviour of stainless steel members were investigated. It was known for many years that stainless steel has a much better fire performance than carbon steel, nevertheless, no systematic study was made to clarify the fire behaviour of stainless steel members used in buildings. To provide a technical basis for fire design of stainless steel members both material mechanical properties of different stainless steel grades and the related structural behaviour are investigated not only through various experimental works but also from numerical simulations.

Table 3. Typical values of the thermal properties of relevant materials for the compartment envelop

Material	**Temperature (°C)**	**λ (W/m/K)**	**ρ (kg/m3)**	**c_p (J/kg°K)**
Ceramic Wool	20	0,035	128	800
	200	0,06	128	900
	500	0,12	128	1050
	1000	0,27	128	1100
Cement	20	0,0483	200	751
	250	0,0681	200	954
	500	0,1128	200	1052
	800	0,2016	200	1059
Calcium Silicate	20	0,0685	450	748
	250	0,0786	450	956
	450	0,0951	450	1060
Bricks	20	1,04	2000	1113
	200	1,04	2000	1125
	500	1,18	2000	1135
	1000	1,41	2000	1164

A huge number of tests have been carried out in order to investigate mechanical properties of stainless steel at elevated temperatures (figure 5). Based on the experimental results obtained for different steel grades, an analytical investigation was made which has led to the establishment of a mathematical model for describing stress-strain relationships of stainless steel at elevated temperatures.

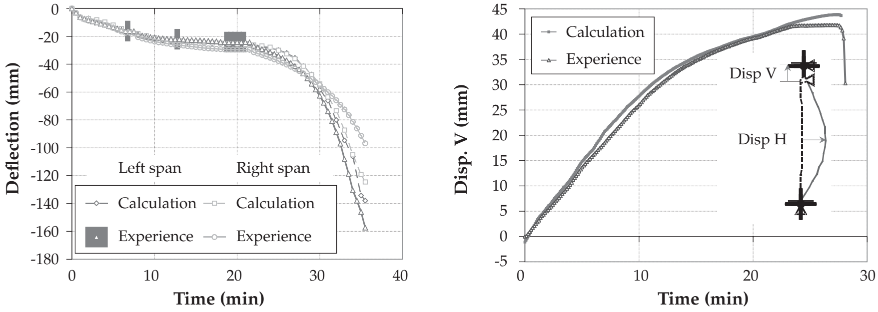
The relevant parameters necessary to cover a temperature range from 20 °C to 1000 °C have been given for five stainless steel grades studied in these research projects. The stainless steel material model was then used to simulate the fire behaviour of various kinds of structural elements; in general their comparison with test results gives good agreement [31] (figure 6). The material model for stainless steel at elevated temperatures obtained in these projects has been incorporated in the informative annex C of the fire part of Eurocode 3 for steel structures [32].



Device for tensile tests

Anisothermal test results of stainless steel

Figure 5. Anisothermal test of stainless steel at elevated temperatures



Continuous stainless steel beam

Stainless steel column

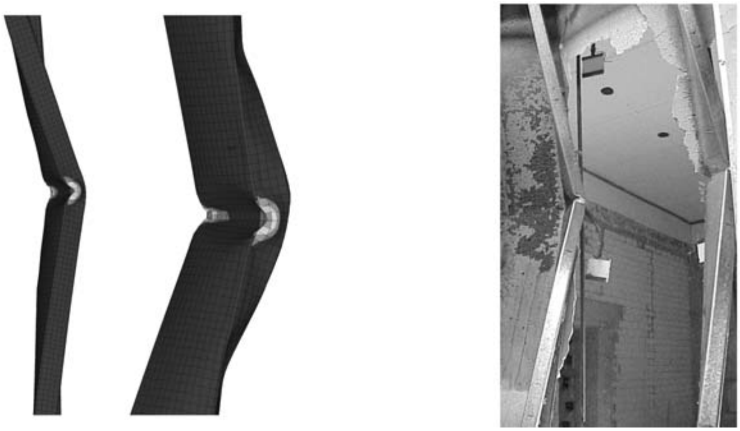
Figure 6. Comparison between fire tests of stainless structural members and numerical modelling

In parallel to above research projects on stainless steel, important works have been carried out for investigating the fire behaviour of cold formed lightweight steel structures [33, 34, 35] because of their increasing use not only as non-load bearing structural members, such as in fire partition walls, but also as load bearing structural members such as in housing or rack structures. The main objective of these works was to get deep information about the performance of this type of steel structure subjected to fire condition. The main feature of such structure elements is their important sensitivity to local buckling due to the very thin wall sections, and in the ENV version of Eurocode 3, no calculation rule, except a fixed critical temperature of 350 °C, is provided.

The research project dealt with the following items

- mechanical properties of cold worked lightweight steels at elevated temperature,
- assessment of the fire behaviour of fully engulfed lightweight steel studs,
- assessment of the fire behaviour of steel studs maintained by boards with fire on one side of the partition,
- development of design rules to be implemented into the European standards.

The advanced numerical modelling developed in this research project, taking account of corresponding material model, is fully valid for predicting the fire behaviour of cold worked lightweight steel (figure 7). For the time being, the results of this work has been partially included in informative annex E of the fire part of Eurocode 3 [32].



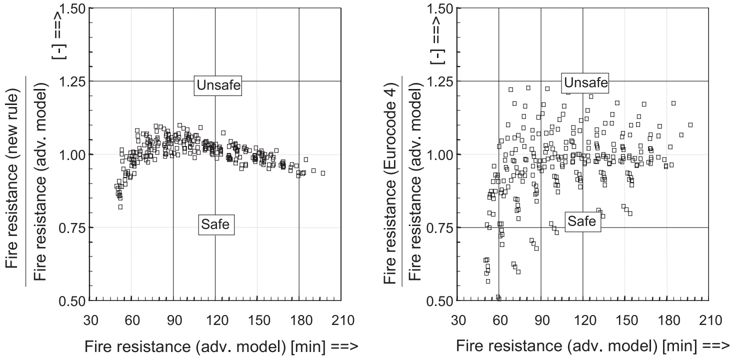
Deformed shape simulated for steel stud Deformed shape of studs in fire test

Figure 7. Comparison between fire tests of cold worked lightweight steel structural members and numerical modelling with developed material model

4 Fire behaviour of composite structures

The steel and concrete composite structures have shown important advantages regarding the fire performance. The first version of the fire part of Eurocode 4 appeared in the middle 80's and should be at that time the first code in the world in which a full design procedure is provided. Although different design rules have been available in this version, some of them remained still either incomplete or not fully accurate. For that reason, an important research project has been conducted from 1988 in which the first design rules of Eurocode 4 with respect to steel and concrete composite slabs and beams were fully investigated by means of both experimental and analytical studies [36]. This project sponsored by ECSC, accompanied by other independent works [37, 38], has led to improve design rules for composite slabs and beams.

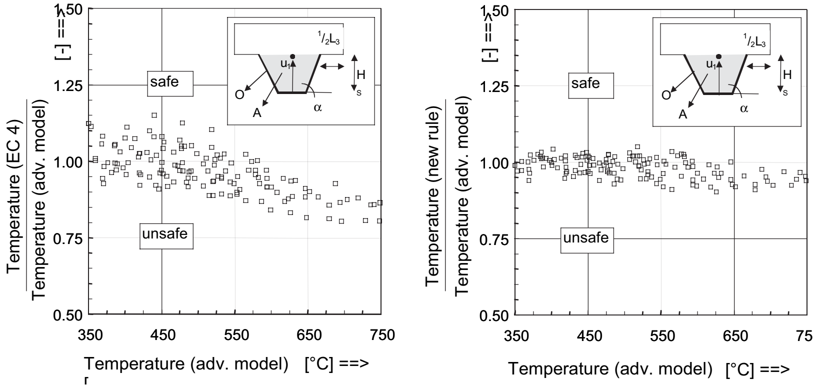
Regarding steel and concrete composite slabs, the design rules derived from above research works allow to give much more accurate results compared to old design rules of the ENV version of the fire part of Eurocode 4. For the insulation criterion, figure 8a a comparison is made between the outcomes of the new simple calculation method and of an advanced calculation model. A similar comparison, based on the rules given in the previous version of the fire part of the Eurocode 4, is presented in figure 8b.



(a) assessment according to new rule (b) assessment according to old rule

Figure 8. Comparison of simple calculation methods for the insulation criterion of composite slabs to the outcomes of an advanced calculation model [37]

Another example concerns the temperature assessment of reinforcing steel in composite slabs; in figure 9, one can find that the new rule gives better estimation than the old rules of Eurocode 4. All these rules and, in addition, the rules related to mechanical resistance model have been incorporated in the latest version of the fire part of Eurocode 4.



(a) assessment according to old rule (b) assessment according to new rule

Figure 9. Comparison of the simple calculation methods for temperature of reinforcing steels of composite slabs to the outcomes of an advanced calculation model [37]

Another steel and concrete composite member dealt with in above research project concerns composite beams. In the old version of fire part of Eurocode 4, the design rules permitted only to predict the fire resistance of simply supported and full shear connected composite beams. However, in reality, more and more composite beams are made with partial shear connection. In addition, the use of continuous composite beams could provide much better fire resistance than simply supported beams. As a consequence, the research work performed was based on both fire tests and numerical modelling, providing a solid technical background for the establishment of design rules regarding shear connection resistance (figure 10), and regarding the mechanical resistance of composite beams with hogging moment (figure 11). The derived corresponding design rules have been included in current section 4 of the main part and informative annex E of Eurocode 4 [39].

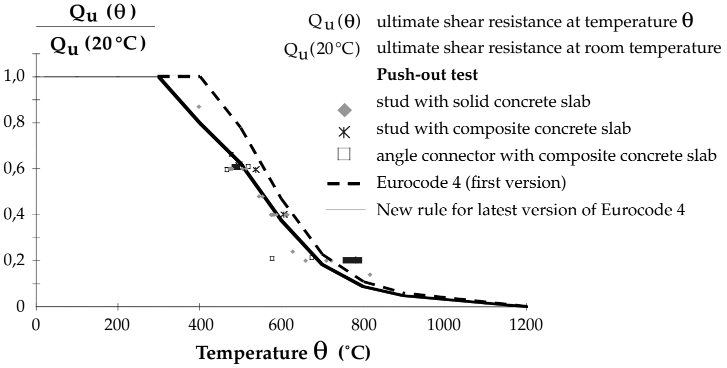


Figure 10. Shear of resistance of connectors at elevated temperatures

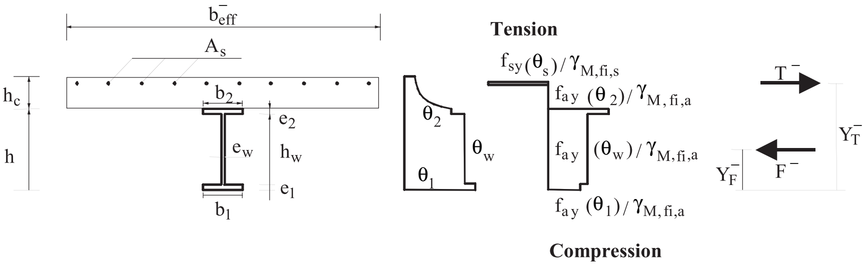


Figure 11. Design rules for calculation of hogging moment resistance

5 Conclusions

Over 15 years or so, a team of European experts were able to develop new calculation rules for the behaviour of steel and composite structures in any fire situations.
These calculation rules were mainly based of a huge amount of research projects carried out with the sponsoring the ECSC.
Within the last version of the fire part of Eurocode 1 "actions in case of fire", it becomes obvious that an accurate assessment of the fire safety level of a building needs to consider realistic fire scenarios and that the use of the previous ISO-fire needs to be limited to the ranking of construction products.
The design rules in the last version fire parts of Eurocode 3 and 4 become more accurate and cover more types of structural members in fire situation due to the numerous research projects carried out during last twenty years as presented above. Nevertheless, some work is still necessary to enlarge the application field of Eurocodes for a full available fire safety engineering assessment of steel and composite structures.

Acknowledgement
The authors wish to thank all the fire experts who have worked with enthusiasm and abnegation to allow reaching the current stage of fire parts of Eurocodes and the European Commission for having (and continuing to) sponsored a large amount of research projects.

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