Some Comments on the Parametric Fire Model of Eurocode 1

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ABSTRACT

In this paper, the modifications that have been recently introduced in the parametric fire model of Eurocode 1 are presented. The reasons behind these modifications are given. Some Problems that have been discovered in the present formulation are highlighted, namely the fact that the model is not continuous and the fact that the heat release of wood that has been used for the calibration of the model is not consistent anymore with the value that is now recommended in the Eurocode. A proposal is made that makes the model continuous. A new calibration of this modified model has been made on the base of the now recommended value of the heat release of wood with comparison to the results of some 50 full scale experimental fire tests.

Keywords: *Fire, Eurocode, Parametric Fire Model*

INTRODUCTION

For the fire resistance of structural members or structural systems, nominal temperature-time curves are very useful for comparing different members against each other or when a classification has to be established with regard to predefined criteria. It has yet to be realised that these curves bear a very weak relationship with the situation that could develop in a real fire. The only link lies in the choice that can be made between different curves for different generic situations such as, for example, the external fire curve for the outside of separating external walls, the ISO fire curve for a fully developed fire in a compartment, the hydrocarbon fire curve for representing effects of an hydrocarbon type fire, and the increased hydrocarbon curve or the RWS fire curve for fires in a tunnel. Within any of these generic situations, a unique fire curve is systematically used, and the influence of various physical parameters is not accounted for, although they are known to affect significantly the duration and the intensity of real fires.

Equivalent time models are an attempt to take into account the physical parameters that influence the duration and the intensity of the fire. Such model give, for any combination of the physical parameters, a duration of a nominal fire supposed to have the same heating effect as a real fire. Numerous models have been developed in the past [1], essentially for representing fully developed fires in a compartment, in which case the nominal fire that they are related to is the standard ISO 834 fire. The problem is that such models are not independent of the type of structure that is considered; in other words, a model developed for unprotected steel members may not be valid at all for reinforced concrete or for timber members [2]. Also, no information is available on the real duration and intensity of the real fire that could develop in a particular situation; only the equivalent duration of the nominal fire is given. For these reasons, equivalent time models are not considered as up to date anymore. Although such a model is proposed in the informative annex F of the most recent version of Eurocode 1 [3], it is likely that utilisation of this model will not be accepted in several Member States when they each write their own National Application Document.

Parametric temperature-time curves are determined on the basis of fire models and take into account the specific physical parameters defining the conditions in the fire compartment. They are very appealing because they offer the advantage that the most important physical parameters can be accounted for without relying on complex differential equations that require a sophisticated computer software to be solved. Numerous parametric models have been proposed in the literature, including some recent developments [4]. Most of these models have been derived for the situation of fully developed fires in a compartment. They differ from each other by the equation(s) that describe(s) the evolution of the temperature as a function of time and by the way that the most important parameters are considered. In most of these parametric models, as well as in the equivalent time models, the physical phenomenon that are taken into account are systematically the same.

- One parameter accounts for the fire load in the compartment. Usually, only the quantity of fuel is considered.
- One parameter accounts for the ventilation conditions in the compartment, i.e. for the openings such as windows and doors that allow the inflow of fresh air and the outflow of combustion gases.
- One parameter accounts for the nature of the walls, ceiling and floor of the compartment, because of the influence of the energy that is absorbed by these elements during the course of the fire.

Such a parametric fire model was present in the ENV version of Eurocode 1 [5]. This model has been modified when Eurocode 1 has been transformed from the status of ENV [5] to EN [3]. Some research works have been undertaken at the University of Liege in collaboration with the University of Naples Federico II in order to verify the consequences of these modifications. The results of these research works are reported in this paper.

RECENT HISTORY

When Eurocode 1 was published as an ENV in 1995 [5], its informative annexe B contained a parametric temperature-time model. The main parameters were:

- the fuel load density $q_{t,d}$ related to the total surrounding area of the compartment A_t,
- the opening factor $O = A_v \sqrt{h} / A_t$, where A_v is the area of vertical openings and h is the height of vertical openings,
- the wall factor $b = \sqrt{c \rho \lambda}$, where c is the specific heat, ρ is the specific mass and λ is the thermal conductivity of the material of the surrounding walls of the compartment.

Figure 1 shows a schematic view of the temperature-time curve produced by this model. The non linear heating phase is given by a sum of negative exponentials. The curve tends toward an horizontal asymptote at the level of 1325°C when time tends toward infinity. The descending branch is linear. The slope of the heating curve depends on the wall factor and the opening factor. The time for starting the cooling phase depends on the fuel density. The rate of cooling depends on all three parameters.

This model was checked by the last author of the present paper against a set of 48 full scale experimental fire tests [6]. The agreement between the model and the experiments was found as very poor when the maximum gas temperature was considered and also when the maximum temperature of a hypothetical unprotected steel section was calculated based on the gas temperature from the model and then from the tests. The agreement was somehow better when the maximum temperature of a thermally protected section was considered.

A first reason of the poor correlation was found in the rather inappropriate equation that was given in the Eurocode for calculating the wall factor in walls made of several layers of different materials. A proposal was made in [6] for another equation that better reflects the amount of energy absorbed by multi layer walls. This proposal can be introduced and used in any compartment fire model that is based on the same concept of heat penetration in infinitely thick walls.

Another reason was found in the fact that the Eurocode model was based on the assumption that the fire in the compartment is in the air control regime. An increase of the opening factor will result in a faster combustion of the fuel load with, as a consequence, a faster increase rate of the temperature during the increasing phase and a shorter duration of this increase phase. Figure 2, for example, shows the temperature-time curves obtained in a compartment 5x4x2,60 m^3 in size with a wall factor b = 1000 and a fuel load density of 560 MJ/m^2 of floor area (≈ 40 kg of wood/m^2) corresponding to $q_{t,d}$ = 129 MJ/m^2. The opening factor has been given different values covering the range of admissible values according to the Eurocode, i.e. from O = 0,02 (e.g. a window with B x h = 1,7x1,0 m^2) to O = 0,20 (e.g. a window with B x h = 5,0 x 2,29 m^2 that is, one of the long walls nearly completely open).

It can be seen on this Figure that, with the highest opening factor, the increasing phase was supposed to be finished after 5 minutes which means implicitly that approximately 70% of the whole fire load made of 800 kg or, roughly speaking, 2m^3 of wood is supposed to be consumed in 5 minutes. This is obviously not realistic. A modification was proposed that can be linked to the physical fact that any fire load, whatever the amount of openings in the copartment, needs a minimum amount of time to be burnt. If, for the same example, the duration of the increasing phase is estimated to be 15 minutes, then the curves of Figure 2 are modified as shown by Figure 3. In this proposal, the equation giving the duration of the increasing phase t_d is Eq. 1.

$$t_d \quad = \quad \max\left(0.13\times10^{-3}\, q_{t,d} \big/ O \ ;\ t_{\lim} \right) \tag{1}$$

with t_{lim} the maximum duration of the increasing phase in fuel controlled conditions.

Another modification was proposed in [6] in order to reflect the fact that, for opening factors higher than the one leading to the stoechiometric combustion, the excess of air that circulates through the openings without being involved in the combustion nevertheless has an influence in the sense that it vents the compartment.

When the Eurocode was changed from an ENV into an EN, the draft team took on board the proposal made in [6]. The same data base of 48 experimental tests plus 2 additional test results were used as a reference and compared [7] to the results produced by the modified Eurocode model and with two other parametric fire models, see [8] and [9]. The correlation was best with the modified Eurocode model, which comes as no surprise because this model had been calibrated against the first series of 48 experimental tests among the 50 tests now under consideration but, at least, the project team had verified that a better agreement would not be provided by these two other proposals.

When doing their comparisons for the conversion to EN, the research group of the ARBED company found that the fit between the model and the test results would even be improved if an apparently minor modification was introduced. In fact, the coefficient $0,13 \times 10^{-3}$ that appeared in Eq. 1 was replaced by two different values:

- $0,20 \times 10^{-3}$ would now be used in equation A.7 of the Eurocode that gives the duration of the heating phase, t_{max} (also in Eq. A.12 that gives $t^*_{\max}$) and
- $0,10 \times 10^{-3}$ would be used in equation A.9 that gives the opening factor to be considered in case of fuel controlled regime, O_{lim}.

The ECCS sponsored FIRENET project provided the opportunity to have a close look at the Eurocode parametric model since it has been published as an EN in 2002. The results of this analysis are reported hereafter.

DISCONTINUITY

It can be demonstrated mathematically that the split of the unique value of the coefficient of Eq. 1 into two different values, depending on the equation where this coefficient is used, has introduced a discontinuity in the model at the transition between the air controlled regime and the fuel controlled regime.

Such a discontinuity in the results given by the model can be produced not only by a slight variation of the opening factor but also by a slight variation of the fire load. This is shown by Figure 4 and Figure 5. These Figures have been drawn for a compartment with b = 1000 J/m²s$^{0.5}$K. Figure 4 shows the discontinuity in the evolution of the maximum temperature as a function of the fire load when the opening factor is fixed to 0,10 m$^{0.5}$, see the curve noted "EB 1991-1-2". Figure 5 shows the discontinuity in the evolution of the maximum temperature as a function of the opening factor when the fire load is fixed to 200 MJ/m², see the curve noted "EB 1991-1-2". It can be observed that the transition from the fuel controlled regime (left hand section of the curves) to the air controlled regime (right hand part of the curves) is not continuous.

The discontinuity is even more striking on Figure 6 that presents the two temperature-time curves produced by the model for two values of the fire load that are nearly identical (O = 0,10 m$^{0.5}$).

This discontinuity does not seem to be linked to the physics of a compartment fire. It is not observed when the situation in the compartment is calculated by more sophisticated models such as, for example, zone models. It may also lead to the uncomfortable situation where a designer ends up with an apparently satisfactory situation, not realising that a slight variation of one of the input parameters might change the situation completely. In fact, owing to the uncertainty and the variability that is linked to the input variables introduced in a fire model, it is always wise to make a sensitivity analysis but this possibility is not always present in real live projects because of time and budget constrains.

HEAT OF COMBUSTION

When analysing the Eurocode parametric fire model of EN during the research works presented here, one of the task was to calculate the temperature-time curve as proposed by the Eurocode fire model for all of the tests that form the data base mentioned previously. For these tests, the maximum gas temperature was noted first, as predicted by the model, then as recorded during the test. In a first step, it was impossible for the authors of this paper to reproduce the values presented in [7]. The temperatures calculated by the authors were systematically lower than those presented in [7]. The difference was around 100°C for maximum temperatures in the range 400-500°C and up to 200°C for maximum temperatures in the range 1000-1200°C. This discrepancy was particularly embarrassing because it is precisely stated in the Background Document that the model of ENV has been preferred to other models because of the good agreement between the model and the experimental tests.

A possible error in the computer program established for quickly calculating the temperature-time curve of the Eurocode model was first ruled out by comparing for different cases the curves predicted by this model and by two other independently written software.

It appeared finally that the reason of the discrepancy lies in the value used for the heat of combustion of wood. The fire load of the experimental tests was reported in terms of kg of wood. In the text of the Background document, it is written that *"… heat of combustion of … wood … is equal to 19 … (14 … if the combustion factor m is considered)*.". This is because, based on this text, the value of 14 MJ/kg was used in our calculations that the predicted temperatures were lower. In fact, all values of the Background Document have been obtained on the base of a value of 18 MJ/kg. As a matter of fact, this value was recommended for particle boards in the ENV version of Eurocode 1 [5]. When this higher value is introduced for transforming the fire load from kg of wood to MJ, the calculated temperatures are then exactly those reported in [7].

In the more recent EN version, the recommended value for the effective heat of combustion of wood is now 14 MJ/m². If we accept that this value proposed in the most recent document reflects reality better than the previous value, then the EN Eurocode parametric fire model has been calibrated on the base of a value that is too high. If the model calibrated in that way is now used in a compartment when the fire load is known by its content in term of kg of wood and the up to date value of the heat of combustion is used, the predicted temperatures will be lower and the situation is thus on the unsafe side.

Even if the fire load is directly given in terms MJ of fuel per m² without any reference to the type of fuel, as found for example in design tables that give the design fire load as a function of the occupation type of the compartment, the situation is also on the unsafe side.

The situation is depicted schematically in Figure 7. The maximum gas temperature in the compartment, T_{max}, is an increasing function of the fire load, Q, as shown for example on Figure 4. Lest us assume a particular fire test characterised by the maximum temperature T_{test} . If the fire load is calculated from the multiplication of the wood content by a heat of combustion of 18 MJ/kg, the obtained value can be noted as Q_1 on the Figure. The calibration of the fire model will then be done in such a way that the model leads to a curve like the one noted "1" on the Figure, because it has to pass through the point A. If the same situation is modelled at a later stage with the same wood content but with a reduced value of the heat of combustion equal to 14 MJ/m², the calculated fire load will be lower, for example Q_2 on the Figure, and the maximum temperature corresponding to Point B will be yielded by the model, that is, a lower temperature than what the test has indicated. In fact, the model should have been calibrated on the base of Point C, in which case the response of the model would be represented by curve "2".

If, for a practical design, the fire load is directly given in terms of MJ/m² depending on the type of occupancy of the compartment, Q_3 for example, the response given by the model calibrated on Point A will be represented by Point D whereas the response given by the model calibrated on Point C will be represented by point E. This indicates that the value chosen for the heat of combustion of wood during the calibration of the model has also an influence on the safety level obtained in a real design when the fire load is directly given in terms of MJ/m².

PROPOSED SOLUTION

It is possible to solve the two problems mentioned previously without completely changing the nature of the parametric fire model of the Eurocode.

The two different coefficients that appear in the equations used to determine the time of maximum temperature of the heating phase, t_{max} and the opening factor to be considered in case of fuel controlled regime, O_{lim} , should obviously be given a unique and single value in order to eliminate the discontinuity in the model.

Using the value of the effective heat of combustion of wood equal to 14 MJ/m² as recommended now in Eurocode 1, this unique value of the coefficient should be calibrated against the data base of experimental test results in such a way that the best possible fit is obtained between the recalibrated model and the tests.

This work has been done for all the available test results and the maximum temperature was taken as the scalar representing each test or calculation. For all tests, the limit time t_{lim} was taken as 20 minutes. The results are summarised in Table I. It appears that the predicted temperature increase with increasing values of the coefficient. The maximum temperature is, in the average, predicted exactly by the model when the coefficient is given the value of 0.14×10^{-3}. The evolution of the maximum temperature as a function of the fire load and of the opening factor with this unique coefficient is presented as the curve noted "New proposal" on Figure 4 and Figure 5.

Figure 8 that shows the evolution of the average value indicates that the tendency is the same when all tests are considered, including some tests that are outside the limits of application of the parametric model according to Eurocode 1, or when only the tests that are inside the limits of application of the model. This may indicate that the field of application of the parametric fire model may be widened but this topic is beyond the scope of this paper.

CONCLUSIONS

The parametric fire model presented in Annex A of Eurocode 1 [3] has been examined.

The fact that two different values, 0.10×10^{-3} and 0.20×10^{-3}, are now used for the coefficient multiplying $q_{t,d}$ in Eq. A.7, A.9 and A.12 leads to a discontinuity in the model. The temperature-time curves are still continuous for any values of the input parameters but a minor variation of the fire load or of the opening factor may lead to two significantly different temperature-time curves.

It has also been found that the value of the heat of combustion of wood that had been used for the calibration of the model, namely 18 MJ/kg, is not consistent anymore with the value of 14 MJ/kg that is now proposed in Annex E of the Eurocode.

The discontinuity in the model disappears if a single value is used for the coefficient multiplying $q_{t,d}$ in Eq. A.7, A.9 and A.12. This coefficient has been calibrated in such a way that the model gives, in the average, the same maximum temperature as the one observed in a series of around 50 experimental full scale fire tests. The value that gives the best fit between the model and the tests is 0.14×10^{-3}.

ACKNOWLEDGEMENT

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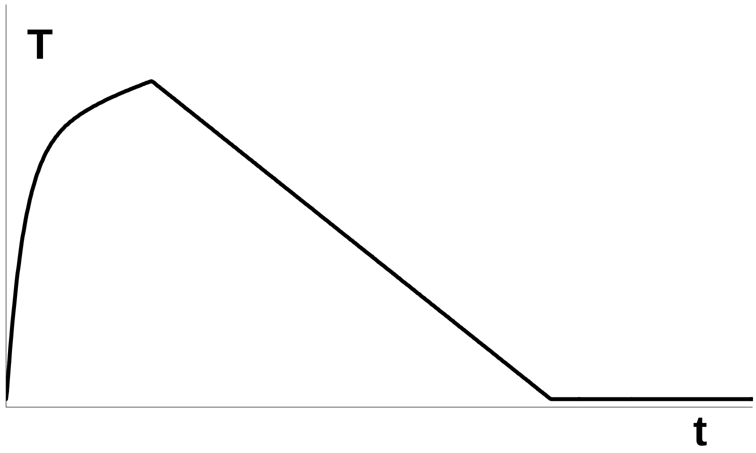

Figure 1: shape of the temperature-time curve of the Eurocode parametric fire model

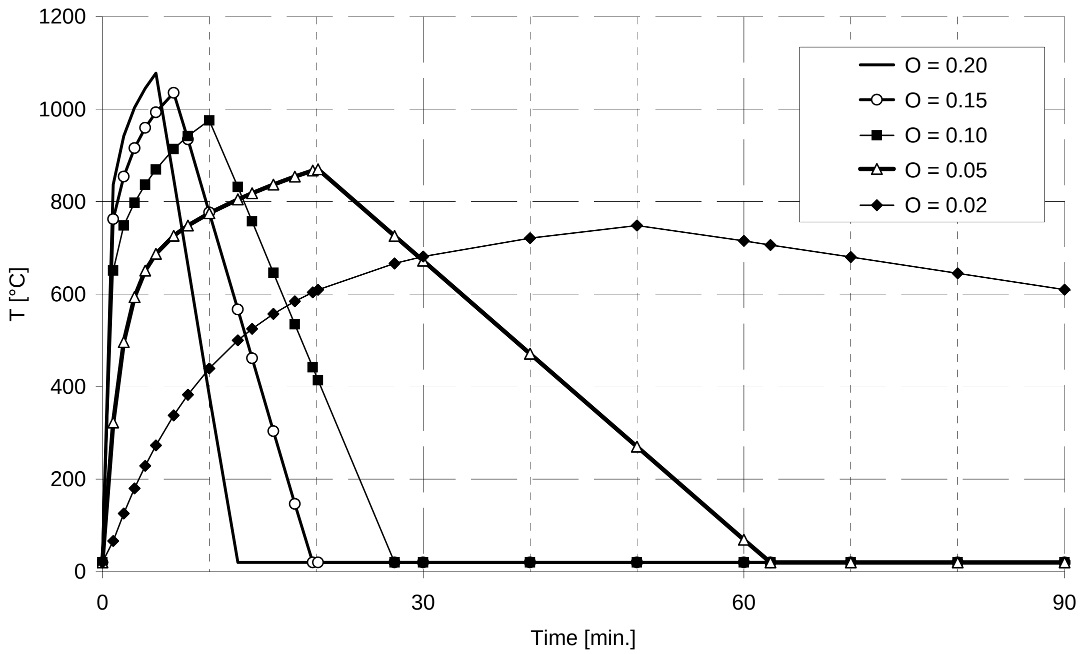

Figure 2: temperature-time curves according to ENV 1991-2-2

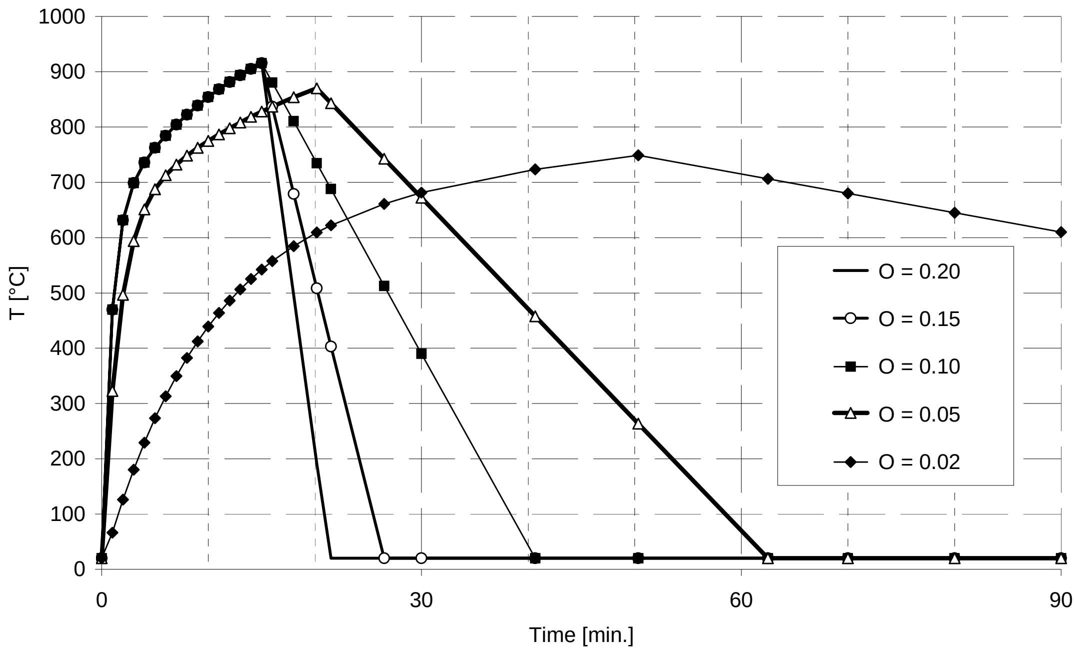

Figure 3: proposal for the fuel controlled regime

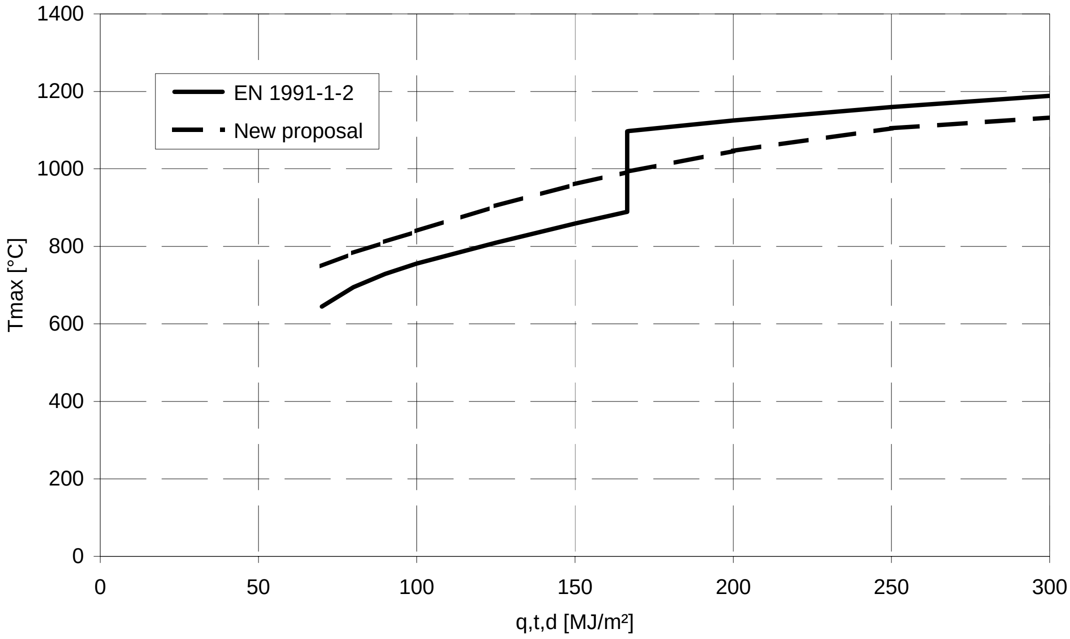

Figure 4: discontinuity for a variation of the fire load

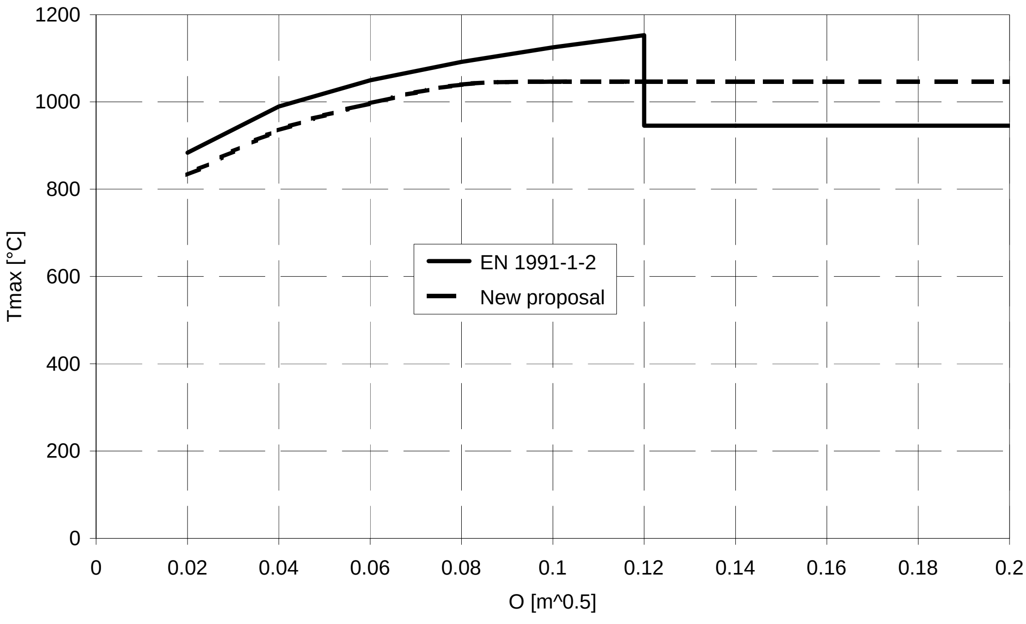

Figure 5: discontinuity for a variation of the opening factor

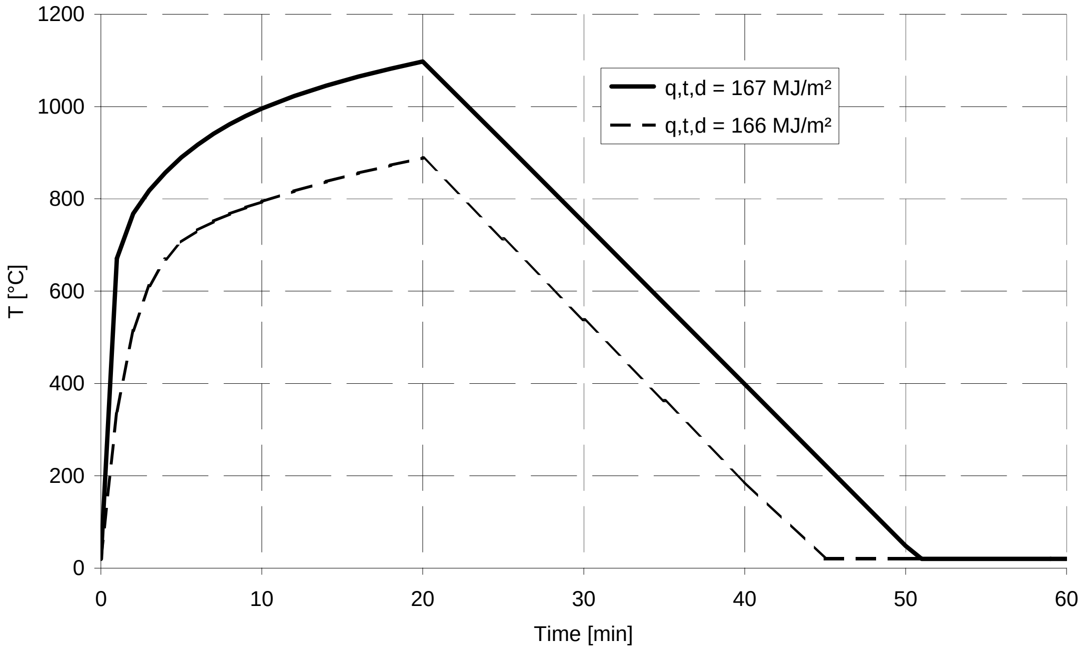

Figure 6: two different curves for nearly the same fire load

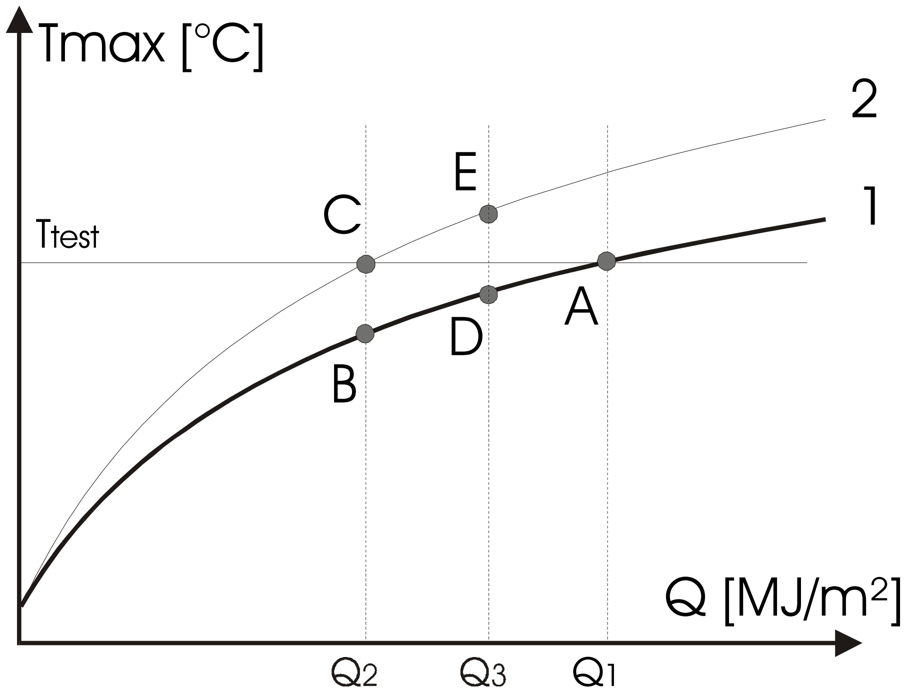

Figure 7: maximum temperature as a function of the fire load

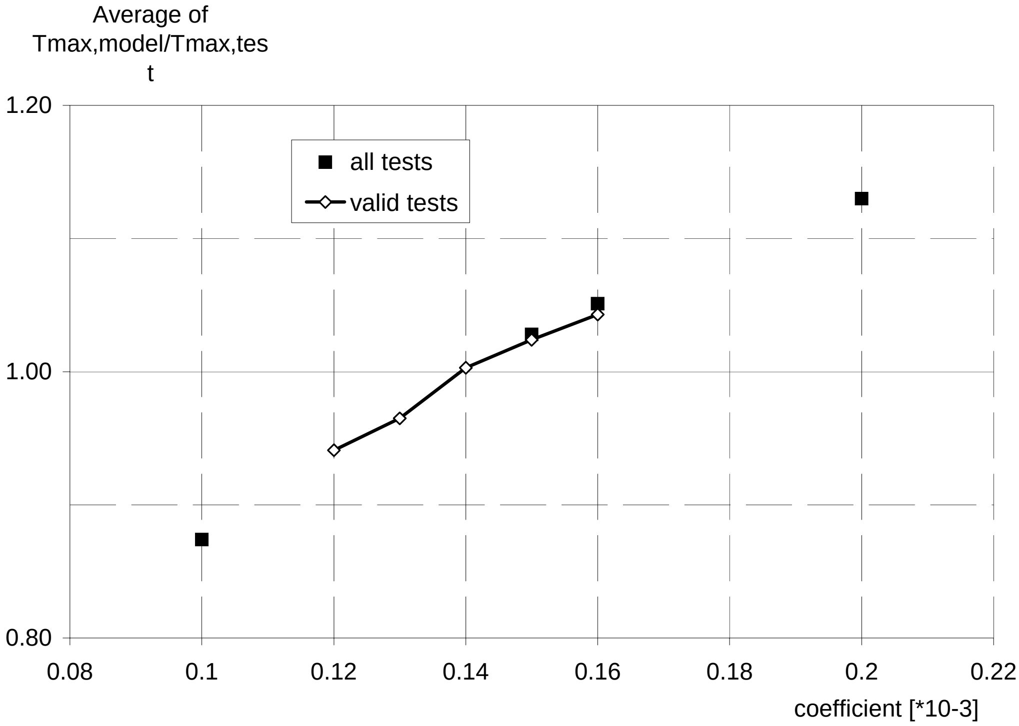

Figure 8: average value as a function of the coefficient

Figure captions

Figure 1: shape of the temperature-time curve of the Eurocode parametric fire model

Figure 2: temperature-time curves according to ENV 1991-2-2

Figure 3: proposal for the fuel controlled regime

Figure 4: discontinuity for a variation of the fire load

Figure 5: discontinuity for a variation of the opening factor

Figure 6: two different curves for nearly the same fire load

Figure 7: maximum temperature as a function of the fire load

Figure 8: average value as a function of the coefficient

Value of the coefficient	Average value		Standard deviation	
	Valid tests (45 to 50 tests)	All tests (67 tests)	Valid tests (45 to 50 tests)	All tests (67 tests)
0.10×10^{-3}	-	0.874	-	0.075
0.12×10^{-3}	0.941	-	0.115	-
0.13×10^{-3}	0.965	-	0.117	-
0.14×10^{-3}	1.003	-	0.141	-
0.15×10^{-3}	1.024	1.028	0.145	0.138
0.16×10^{-3}	1.043	1.051	0.148	0.154
0.20×10^{-3}	-	1.130	-	0.210

Table I: ratio Tmax,model/Tmax,test (- means: calculation not performed)