CASE STUDIES OF A NEW SIMPLIFIED NATURAL FIRE MODEL AND SAFETY CONCEPT FOR STRUCTURAL FIRE SAFETY DESIGN

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INTRODUCTION

The structural fire safety design in most countries is usually carried out on the foundation of the material requirements of the building codes. This prescriptive design bases on the well-known standard temperature-time curve and simplifies the fire exposure to the building elements. Importance such as fire load, ventilation and geometry of the fire compartment are not considered. An alternative design-way is the performance-based design on the basis of natural fires which is especially applied for special complex buildings such as airports, railway stations, big assembly halls etc. The performance based design of construction elements is conducted by Eurocodes and the National Annex. Due to some deficiencies in the methods of the annexes in Eurocode 1-1-2 for the German National Annex a new simplified natural fire model for fully-developed compartment fires was developed.

By means of an example it is shown how to evaluate the relevant fire actions of a natural fire to the structure on the basis of Eurocode 1-1-2 and the German National Annex [DIN, 2010].

1 EUROCODE 1-1-2 ANNEX A

The standard temperature-time curve was developed in the 1930s summarising data from fires in residential, office and commercial buildings. The curve should cover most of the potential courses of fires in common buildings. The standard temperature-time curve is the basis of the prescriptive fire safety design and leads in most cases to an overestimation of the thermal action to the structure. For a performance-based design in Eurocode 1-1-2 natural fire models are available with which the realistic temperature-time development depending on fire load, ventilation conditions and geometry can be obtained.

The simplified natural fire model published in Eurocode 1-1-2, annex A however in some cases provides an unrealistic temperature increase and decrease [Zehfuss and Hosser, 2007]. For this reason the annex A-method was not approved in most CEN-countries. The most critical point is that the annex A-method has no temporal connection with the rate of heat release of Eurocode 1-1-2 annex E. This deficiency will be clarified by comparing the parametric temperature-time curve according to Eurocode 1-1-2 with the test results of [Schleich, 2000] (Fig. 1). Obvious is the discrepancy between the temporal course of the parametric temperature-time curve and the rate of heat release according to Eurocode 1-1-2 annex E. The latter achieves its maximum after 30 minutes and declines after 43 minutes. The temperature-time curve and rate of heat release neither match with each other nor are they temporally congruent.

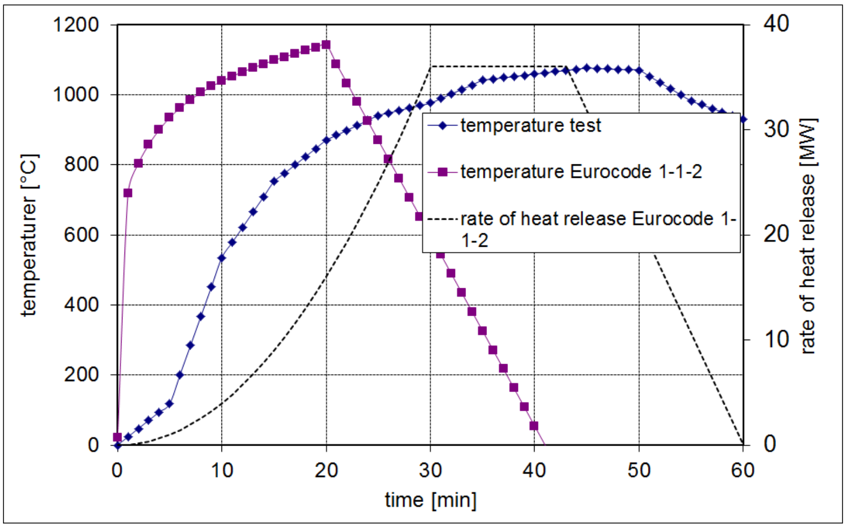

Fig. 1 Temperature-time curve and rate of heat release according to Eurocode 1-1-2

2 NATURAL FIRE MODEL IBMB PARAMETRIC FIRE CURVES

2.1 General

The Eurocode 1-1-2 annex A-method in Germany was not approved by the building authorities due to the mentioned deficiencies. For the reason that in Germany also a simplified natural fire model is provided the new parametric fire curves based on [Zehfuss and Hosser, 2007] were published in the German national annex.

The new simplified natural fire model of the parametric fire curves [Zehfuss and Hosser, 2007], [Zehfuss and Hosser, 2005] is based on the approach of the rate of heat release. The model was derived on simulations with the zone model CFAST for various boundary conditions vs influencing factors. Fig. 2 shows the qualitative shapes of the rate of heat release due to Eurocode 1-1-2 and the simulated temperature-time curve. The temporal link between these curves is evident.

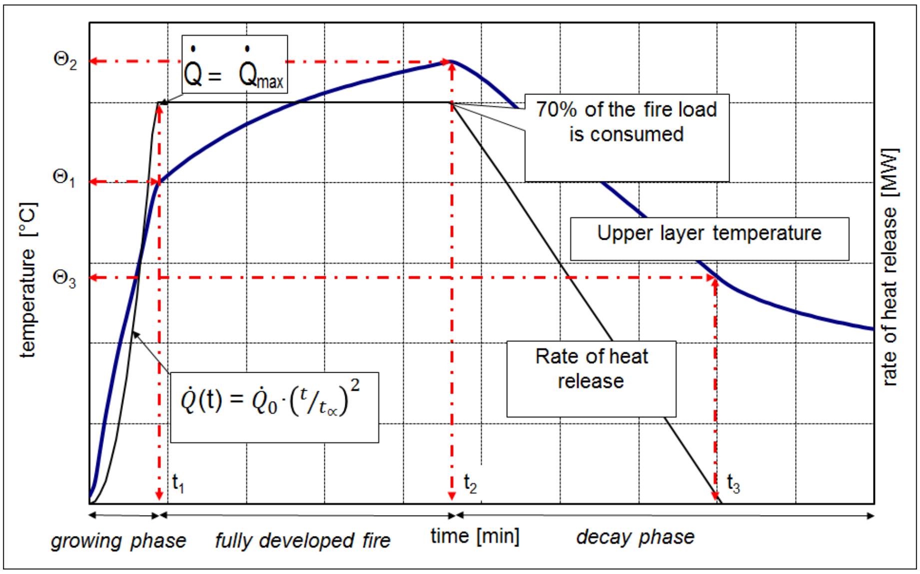

Fig. 2 Approach of heat release and corresponding upper layer temperature (principle)

The parametric fire curves can be divided into three sections (Fig. 3). From the beginning of the fire until t_1 the upper layer temperature increases rapidly. At t_1 the maximum of the rate of heat release is achieved and remains constant until t_2. After t_1 the upper layer temperature enhances increases moderately. As 70 % of the fire load is consumed at t_2, the rate of heat release drops off linearly and the upper layer temperature declines. At t_3 the complete fire load is consumed and the rate of heat release decreases to 0. At this time the upper layer temperature-time curve bends and declines to a lesser extent than before. For the total description of the run of the upper layer temperature-time curve the associated temperatures Θ_1, Θ_2 and Θ_3 have to be ascertained (Fig. 3).

2.2 Rate of heat release

The rate of heat release $\dot{Q}$(t) is given by

$$\dot{Q}(t) = \dot{m}(t) \cdot \chi \cdot H_{net}.$$

whereby

$\dot{m}(t)$: burning rate [kg/s]

The combustion efficiency χ can be assumed as $\chi = 0.7$ for fire loads in residential and office buildings [DIN, 2010]. The net calorific value can be taken as $H_{net} = 17.3$ MJ/kg for wooden fire loads and furnishings. The rate of heat release strongly depends on the ventilation conditions and a distinction is made between ventilation-controlled fires and fuel-controlled fires.
In ventilation-controlled fires according to Eurocode 1-1-2 the maximum rate of heat release can be assumed as:

$$\dot{m}(t) = 0.1\ A_w\sqrt{h_w}\ \text{[kg/s]}.$$

For residential and office buildings in case of a ventilation-controlled fire can be derived by inserting $\chi = 0.7$ and $H_{net} = 17.3$ MJ/kg:

$$\dot{Q}_{max,v} = 1.21\ A_w\sqrt{h_w}\ \text{[MW]}.$$

According to Eurocode 1-1-2 the maximum rate of heat release of residential and office buildings in case of a fuel-controlled fire can be determined as

$$\dot{Q}_{max,f} = 0.25 \cdot A_f\ \text{[MW]}.$$

whereby the maximum burning area A_f [m²] is assumed to be limited to the floor area of the fire compartment.
Fig. 2. illustrates the approach for the rate of heat release [DIN, 2010]. The growth phase is described by the t^2-approach:

$$\dot{Q}(t) = \dot{Q}_0 \cdot \left({}^{t}/_{t_\propto}\right)^2$$

whereby $\dot{Q}_0$ = 1.0 MW and the time of fire growth - with a medium fire growth rate in residential and office buildings - can be assumed as t_α = 300 s.
In the fully-developed fire the quadratic increase in the rate of heat release is replaced by a constant value which is taken as the minimum of the two rates of heat release, for fuel-controlled and ventilation-controlled fires [DIN, 2010]:

$$\dot{Q}_{max} = \text{MIN}\ (\dot{Q}_{max,v}, \dot{Q}_{max,f})$$

When 70 % of the fire load is consumed, the rate of heat release decreases linearly until the fire load is completely burned.

2.3 Parametric fir curves

For a reference fire load density of q = 1300 MJ/m² which is taken as an upper value for residential and office buildings, parametric functions for the temperature-time curve were developed which consider the ventilation conditions, thermal properties of the enclosure and geometry of the compartment. For fire load densities less than the maximum temperature is achieved correspondingly earlier. The appropriate time can be ascertained from the rate of heat release function.

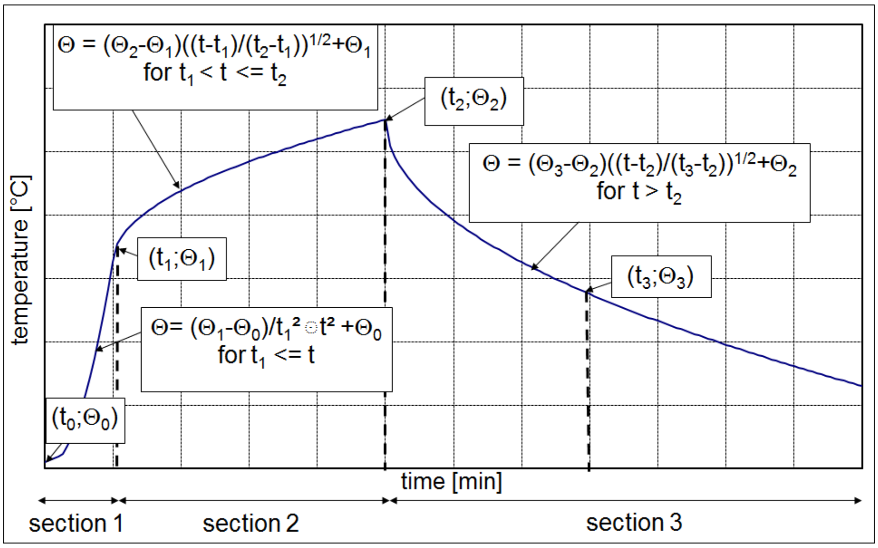

Fig. 3 Mathematical description of the parametric fire curves

A regression analysis for the upper layer temperatures Θ_1, Θ_2 and Θ_3 of ventilation-controlled fires provides the following functions for the reference fire load density of q = 1300 MJ/m² [Zehfuss and Hosser, 2007]:

Θ_1 = -8.75 · 1/O – 0.1 b + 1175 [°C]
Θ_2 = (0.004 b -17) · 1/O – 0.4 b + 2175 [°C]
Θ_3 = -5.0 · 1/O – 0.16 b + 1060 [°C]

with

opening factor	O = $A_w\sqrt{h_w}$ / A_t [$m^{1/2}$],
area of ventilation openings	A_w [m²],
averaged height of ventilation openings	h_w [m],
total area of enclosing components	A_t [m²],
averaged thermal property of enclosure	b [J/m²$s^{0.5}$K].

For fuel controlled fires the following functions for the reference fire load density of q = 1300 MJ/m² were derived [Zehfuss and Hosser, 2007]:

Θ_1 = 24000 k + 20 [°C] for k ≤ 0.04 and Θ_1 = 980°C for k > 0.04,
Θ_2 = 33000 k + 20 [°C] for k ≤ 0.04 and Θ_1 = 1340°C for k > 0.04,
Θ_3 = 16000 k + 20 [°C] for k ≤ 0.04 and Θ_1 = 660°C for k > 0.04.

with

$$k = \left(\frac{\dot{Q}^2}{A_w \cdot \sqrt{h_w \cdot (A_t - A_w) \cdot b}}\right)^{1/3}$$

maximum rate of heat release $\dot{Q}$ [MW]

The functional form of the parametric fire curves in the three sections is depicted in Fig. 3.

3 EXAMPLE OF APPLICATION

The application of the new simplified natural fire model of German national annex [DIN, 2010] is shown by the example of an office room. The required input data is listed below:

Floor area of fire compartment	$A_f = 16$ m²
Height of fire compartment	H = 3.00 m
Ventilation factor	$A_w\sqrt{h_w} = 12.65$ m$^{3/2}$
Opening factor	O = 0.158 m$^{1/2}$
Total area of the enclosing components	$A_t = 80.0$ m²
Fire load density $q_x = 511$ MJ/m²	$Q_{511} = 8176$ MJ
averaged thermal property of enclosure	b = 1500 J/(m²s^{0,5}K)

rate of heat release according to Eurocode 1-1-2 and German national annex:

$$\dot{Q}_{max} = \text{MIN}\,(\dot{Q}_{max,v}, \dot{Q}_{max,f}) = \text{MIN}\,(1.21 \cdot A_w\sqrt{h_w};\ 0.25A_f) = \text{MIN}\,(15.31;\ 4.0)$$

$\dot{Q}_{max} = \dot{Q}_{max,f} = 4.0$ MW => fuel-controlled fire.

Parametric fire curve for reference fire load density of q = 1300 MJ/m²:

$Q = q \cdot A_f = 1300 \cdot 16.0 = 20800$ MJ,

$t_1 = 600$ s = 10 min; $Q_1 = 800$ MJ

$Q_2 = 13760$ MJ; $t_2 = 4040$ s ≈ 67 min

$Q_3 = 6240$ MJ; $t_3 = 7160$ s ≈ 119 min

for $q_x = 511$ MJ/m²:

$Q_{2,511} = 4923$ MJ; $t_{2,511} = 1831$ s ≈ 31 min

$Q_{3,511} = 2453$ MJ; $t_{3,511} = 3057$ s ≈ 51 min

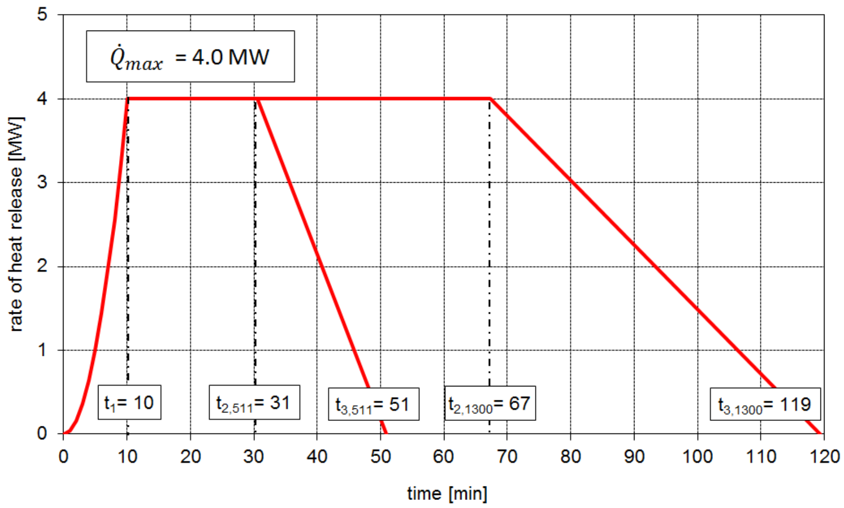

Fig. 4 Rate of heat release example fire in office room

For a fuel-controlled fire it can be derived:

$$k = \left(\frac{\dot{Q}^2}{A_w \cdot \sqrt{h_w} \cdot (A_t - A_w) \cdot b}\right)^{1/3} = 0.0195$$

$\Theta_1 = 24000\ k + 20 = 565°C$,
$\Theta_2 = 33000\ k + 20 = 769°C$,
$\Theta_3 = 16000\ k + 20 = 383°C$.

For the present fire load density q_x = 511 MJ/m² it can be obtained:
$\Theta_{2,511} = 689°C$,
$\Theta_{3,511} = 316°C$.

Fig. 5 shows the parametric fire curve compared to the computed upper layer temperature-time of the advanced natural fire model CFAST and the standard temperature-time curve. The deviation between parametric fire curve and CFAST results are marginal. The new simplified natural fire model of the parametric fire curves can describe the temperature development of a natural fire with a good accuracy.

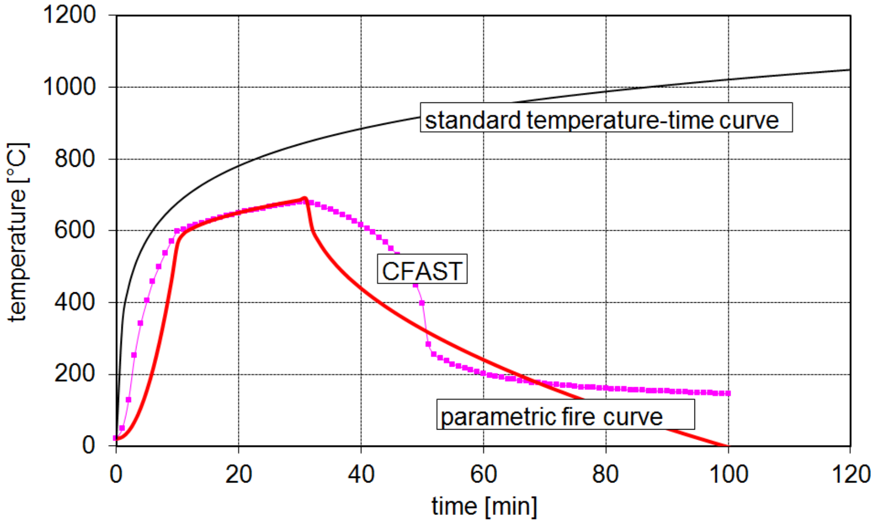

Fig. 5 Comparison of parametric fire curves in German national annex with CFAST results and standard temperature-time curve for an office room

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