Safety concept for structural fire design – application and validation in steel and composite construction

P. Schaumann[1], J. Sothmann[2], C. Albrecht[3]

[1,2] Leibniz University Hannover, Institute for Steel Construction, Hannover, Germany
[3] Technical University of Braunschweig, Institute of Building Materials, Concrete Construction and Fire Protection, Braunschweig, Germany

Abstract

An ongoing research project deals with the validation and application of natural fire models in connection with the new safety concept for structural fire design. In contrast to the original Eurocode 1 safety concept the new safety concept takes into account safety aspects directly in time-dependent design value of the rate of heat release. Based on this rate of heat release the temperature development in the designated area and subsequently the thermal effects to the structure are calculated. Aspects as e.g. sprinklers, size of fire area and availability of the fire brigade are taken into consideration when the safety factors are determined. The research project includes parametric studies for different building types.

The following paper is focussed on open car parks. Probabilistic and deterministic calculations are carried out of a composite beam exposed to a local fire. All calculations are based on the new safety concept and the Eurocode regulations. Temperatures in composite construction as well as the mechanical behaviour at high temperatures are calculated with FEM-models.

Finally, a natural fire design model for open car parks is proposed which provides equivalent design results compared to the existing prescriptive building regulations in Germany.

Introduction

In the middle of the year 2010 the National Annexes (NA) to Eurocodes for structural fire design are going to be published in Germany. In the NA to Eurocode 1 Part 1-2 (EC1-1-2) [1] a new safety concept [2] as well as new parametric temperature-time curves for natural fires [3] are introduced. Both methods have been developed at the Institute of Building Materials, Concrete Construction and Fire Protection (iBMB), TU Braunschweig. These two developments feature an important improvement not only for Germany but also for the further development of European normative regulations.

Figure 1 depicts the heat release rate and the corresponding temperature-time curve. The direct interrelation between both becomes obvious. Deviating from the original EC1-1-2 [4] the calculation of the temperatures is directly based on the curve of the heat release rate, which can be separated in three phases: growing phase, fully developed fire phase and decay phase. Consequently the basic parameters of the heat release rate in the NA to EC1-1-2 are connected to the safety concept, which will shortly be presented in the following chapter.

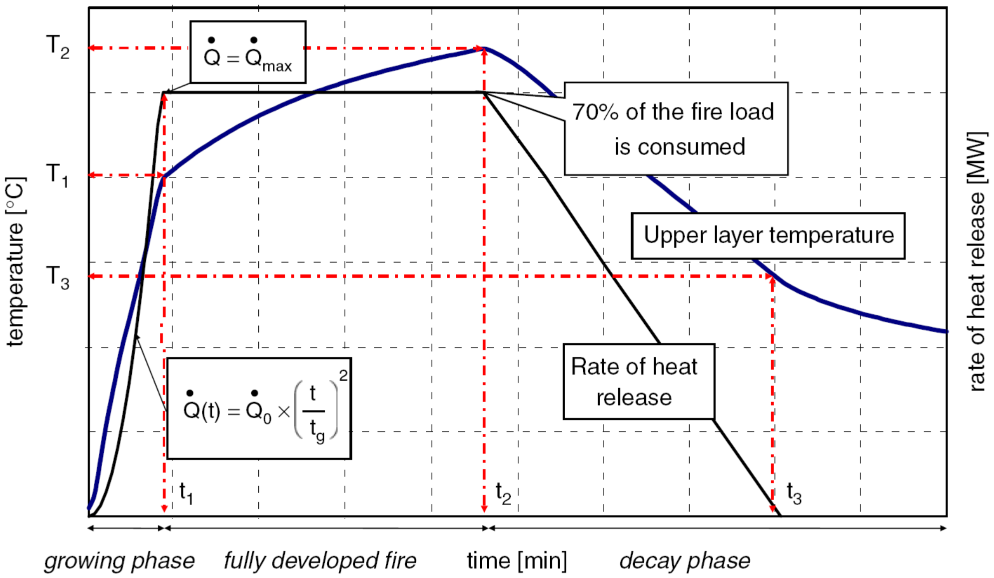

Figure 1 Approach of the rate of heat release and the corresponding upper layer temperature (principle) acc. to Zehfuss/Hosser [2]

This paper presents first results of a research project funded by bauforumstahl, which aims at the application and validation of the new design methods given in NA to EC1-1-2. As structural fire design plays an important role for the competitiveness typical areas of application of steel and composite construction were choosen:

- open car parks
- office buildings and
- assembly halls.

This paper is focussed on the investigations concerning open car parks.

Fire Safety Concept acc. to National Annex of Eurocode 1 Part 1-2

The new safety concept is part of annex BB ´Input data for the application of natural fire models´ [1]. In this annex design values of the fire load $q_{f,d}$ in buildings with different use and design values for the maximum rate of heat release $\dot{Q}_{max}$ for different design fire scenarios are defined. The given design values of the influencing factors on the effects of fire consider the required reliability of structural members and global structures in the accidental event of a fire according to the comprehensive safety concept [2]. For these two design values the respective partial safety factors $\gamma_{fi,q}$ and $\gamma_{fi,\dot{Q}}$ have to be determined in dependency of the respective reliability index β_{fi} as given in Figure 2. The reliability index β_{fi} can be derived from Equation 1.

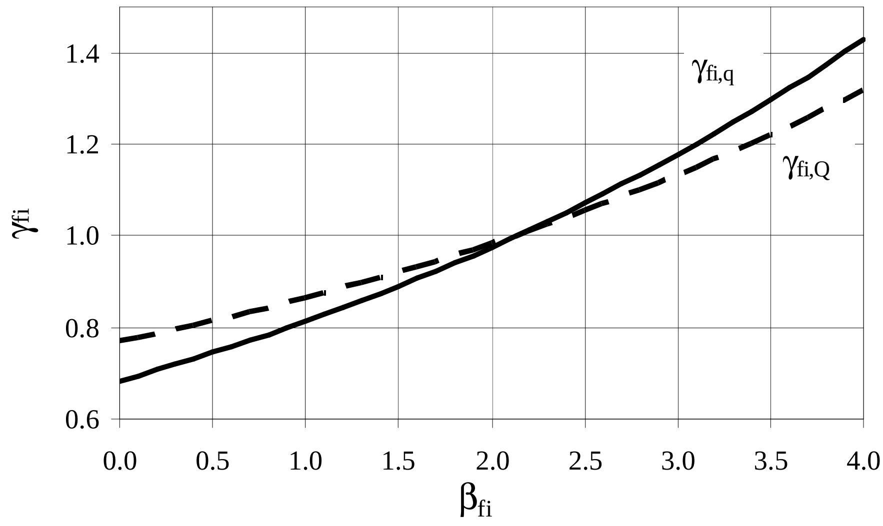

Figure 2 Partial safety factors versus reliability index acc. NA to EC1-1-2 [1]

$$\beta_{fi} = -\Phi^{-1}(p_{f,fi}) \tag{1}$$

where

$p_{f,fi}$ is the target conditional probability of failure in case of fire

Φ^{-1} is the inverse normal distribution.

The probability $p_{f,fi}$ is given by Equation (2):

$$p_{f,fi} = \frac{p_f}{p_{fi}} \tag{2}$$

where

p_f is the target probability of failure in case of fire; recommended values are given in NA to EC1-1-2 [1]

p_{fi} is the probability of occurrence of a fully developed fire

The probability of occurrence of a fully developed fire p_{fi} is given by Equation (3):

$$p_{fi} = p_1 \cdot p_2 \cdot p_3 \tag{3}$$

where

p_1 is the probability of occurrence of an incipient fire per unit and year

p_2 is the probability of failure of manual fire fighting taking into account selfhelp of occupants as well as fire fighting operations of fire-fighters

p_3 is the probability of failure of automatic fire suppression if required.

The necessary input data for determining the above mentioned partial safety factor applying Equations (1) to (3) are provided by NA of EC1-1-2 [1].

Application and validation of structural fire design methods for a composite beam of an open car park

Motivation and basics

According to actual building regulations in Germany no particular fire resistance is required for beams or columns in open car parks. Thus, load bearing structures comprising unprotected steel columns and unprotected steel beams acting compositely with the concrete or composite slabs became a standard construction method for open car parks. This situation is deviating from the situation in most European countries where minimum fire resistances of 60 min or more are required resulting in concrete structures as common standard. Only the requirements in United Kingdom with moderate values of 15 min standard fire resistance may be compared to the German situation. The author demonstrated in [5] that unprotected steel and composite structures are able to fulfil the 15 min fire resistance requirement if design at room temperature and fire conditions is based on the Eurocodes.

To date there are no occurrences or experiences giving reasons to tighten the existing regulations in Germany. Although it is not possible to support this general remark by statistical data for Germany recent investigations [6] carried out in UK in principle confirm this remark. The project took into account both enclosed and open car parks. A review of the UK fire statistics was carried out for the twelve years 1994 to 2005. Is has been found out that car park fires in UK are rare and that there are very few reported injuries and very few fatalities.

Thus, it should be considered how to harmonize the regulations within the European Union. An adoption of the German regulations on open car parks as prescriptive rules in other countries offers only little chances of success. A much more promising option is to develop an appropriate natural fire design approach for open car parks. This could be possible on the basis of the new safety concept for fire design published in NA to EC1-1-2. Therefore, the objective for the research project presented in this paper is to contribute to this development.

The concrete input data concerning geometry, mechanical loads and material properties are taken as an example from a car park recently built by the company Goldbeck (see Figure 3). The car park is located in Bielefeld, Germany. The structure comprises steel columns and steel/composite beams with a typical spacing of 2.50 m and 16.0 m span. To meet the German fire safety requirements for open car parks an open facade area has been designed. This made it possible to execute the steel structure without any fire protection.

Figure 3 Open car park in Bielefeld (©GOLDBECK GmbH)

The following investigations focus on the composite beams. The cross section of the beam consists of a welded I-section (h_a = 445 mm) and a concrete slab with height of 10 cm. The beam is result of an optimization process concerning design and fabrication which has been carried out in recent times. Due to reduced plate thicknesses of web and flanges, the section factor A_m/V of the I-section is 284 m^{-1}. Figure 4 illustrates the beam during fabrication (left) and after construction from an interior view (right).

Figure 4 Composite beam during fabrication (left) and after construction from an interior view (right)

When the load bearing capacity of an individual beam in the fire situation is investigated it may be assumed that it is concerned by car fires in the two adjacent bays. For that reason a fire scenario with two burning cars is reasonable. In reality it can be expected that the two cars burn with a time delay. In the following investigations it is assumed on the save side that both cars burn simultaneously. This assumption causes more severe fires and consequently higher temperatures in the steel construction. In addition to this, a scenario with three burning cars has been investigated as ultimate limit. Fire is mathematically described by the course of the rate of heat release (RHR). In detail the defined fire area, the fire growth rate, the fire load density and the maximum RHR define course of the RHR. Details for natural fire models in open car parks are not defined in EC1-1-2 or in the NA to EC1-1-2. Therefore, suitable assumptions have to be made as a basis for the investigations. Acc. to [7] and [8] for the fire load of a car an average value of 5500 MJ/car with a standard deviation of 550 MJ/car is assumed. With the given RHR the gas temperature-time curves have been calculated according to Eurocode 1 annex C ´Localised Fires´ [4]. It must be made clear that in this case conditions are deviating from the basis of the general fire safety concept. One of the basic assumptions of the concept is that a fully developed fire is looked at in a defined compartment area. This boundary condition is transferred here analogously to a car fire within a defined area.

The gas temperature-time curves have been taken into account for the calculation of the structural response. Both thermal and mechanical analysis has been performed with the finite element program BoFire, which is based on works of Schaumann [9] in the 1980s and enables to simulate the structural behaviour of two-dimensional frame structures in case of fire. Steel, reinforced concrete and composite cross sections can be modelled. BoFire corresponds to an advanced calculation method and includes the material properties of Eurocode 4 Part 1-2 [10]. In the thermal analysis the so called shadow effect has been neglected. This assumption leads to higher steel temperatures and is consequently on the safe side, too. As the beam is considered as an individual member, effects of load redistribution (membrane effects) are not taken into account. Again, this is a conservative assumption.

The investigations described in the following have been carried out in two steps:

Step 1 Investigations on probabilistic basis
Step 2 Proposal of a natural fire design model for open car parks and application

Investigations on probabilistic basis

The objectives of these investigations were to check whether the calculated target conditional probability of failure $p_{f,fi,cal}$ is in range to be expected and to identify the relevant parameters.

For this purpose the required probability $p_{f,fi,requ}$ has to be determined first by applying Equation (2) and (3).

The target probability of failure in case of fire is assumed to be $p_f = 1.1 \cdot 10^{-4}$.

Justification:
Recommended values may be taken from Table BB.5 of NA to EC1-1-2. The values are given in dependency of the use and consequences of failure. Although the use ´open car park´ is not directly given, the according value can be derived by comparison to the uses given is the table. Experience and statistical evidence [6] justify the rating of the consequences of failure to be small.

For solving Equation (3) the factors p_1, p_2, and p_3 are required.

The probability of occurrence of an incipient fire is assumed to be $p_1 = 1.3 \cdot 10^{-2}$.

Justification:
The value depends on the usage and on the area per separated unit. It is assumed that the usage ´open car park´ may be compared to the usage ´industrial building- storage´(see [2]). Typical numbers of parking spaces range between 200 and 500. Assuming that every car takes an area of 20.5 m^2 square meters (including traffic aisles) the gross area ranges between 400 and 1000 m^2. Based on these assumptions the probability of occurrence of an incipient fire is $1.3 \cdot 10^{-2}$.

The probability of failure of manual fire fighting p_2 is given by Equation (4):

$$p_2 = p_{2,1} \cdot p_{2,2} \quad (4)$$

where

$p_{2,1}$ is in general assumed to be 0.5. In this particular case it is assumed that no manual fire fighting by the users is performed ($p_{2,1}$ = 1.0).

$p_{2,2}$ may adopt two possibilities to take public fire brigades into consideration acc. to the German NA to EC1-1-2:
Intervention time < 15 minutes ($p_{2,2}$ = 0.2)
Intervention time > 20 minutes ($p_{2,2}$ = 0.5)
Both options are investigated

The probability of failure of automatic fire suppression is is assumed to be p_3 = 1.0.
Justification:
Normally sprinklers are not installed in open car parks.

This results in the required probabilities $p_{f,fi,requ}$ as given in Table 1:

Table 1: Required probabilities $p_{f,fi,requ}$ and appropriate safety indices

	Intervention time	
	< 15 min	> 20 min
$p_{f,fi,requ}$	$4.2 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$
β_{fi}	1.73	2.12

For the probabilistic assessment a response surface method [11] was used to limit the amount of complex FE-solver runs for the structure. The response surface method interpolates the limit state function – which in this case accounts for bending failure – using a six dimensional surface of best fit for selected support points. For simplification only six important parameters were considered as stochastic variables to keep the computationally expensive solver runs to a minimum. The parameters and the appropriate distributions are given in Table 2. They were chosen from the appropriate Eurocodes [4] and from further literature review [7] and [8].

Table 2: Parameters and distributions

	mean value	**std. dev.**	**var. coeff.**	**unit**	**distribution**
fire load density	5500	550	0.10	MJ/car	normal
RHRmax	5000	500	0.10	kW/car	normal
steel yield stress	400	28	0.07	N/mm²	normal
concrete strength	50	6.5	0.13	N/mm²	log normal
dead loads	7.13	0.713	0.10	kN/m	normal
live loads	3	1.5	0.50	kN/m	normal

The support points of the response surface methodology were chosen systematically using a central composite design [12] and the according values were calculated with the plume equation and with the FE-solver subsequently. Based on the six variables 45 solver runs have to be completed for every time step. The resulting *n*-dimensional interpolation polynomial was used for the evaluation of the reliability using the first order reliability method (FORM). The design point was evaluated and compared to the design point value of the polynomial. If the difference was less than a chosen threshold value, the analysis was finished. Otherwise a new iteration step was performed around the design point with reduced variances. A sensitivity analysis using stepwise regression [13] and the results from the FORM analysis was performed after the first iteration to reduce the number variables for a reduction in solver runs. The methodology is described in detail in [11]. Reducing the number of solver runs only six relevant time steps were evaluated in between which the point of lowest reliability was assumed after a deterministic preliminary investigation.

In the mechanical analysis of the composite beam two static systems are used. The first system is a simple supported beam at normal temperature design as well as in the fire situation. This is valid for the example given in Figure 3 and 4 which is a so called Split-Level-System. If particular conditions are met a change in the system from two simple supported beams arranged behind each other may change into a continuous beam in the fire situation. The conditions are:

- The gap between column and beam has to be limited
- Tensile and compression forces must be transferred from one beam to the other: Tensile forces by reinforcement in the slab; compression forces by contact.

The results $p_{f,fi,cal}$ (dashed line) and $\beta_{fi,cal}$ (solid line) of the reliability analyses for the open car park are presented in Figure 5. In this case a fire with three cars and a change in the static system to a continuous beam is assumed. It can be observed that the calculated safety indices are higher than the required values given in Table 1. Accordingly the calculated probabilities of failure are smaller. Hence it follows that the composite beam will resist a fire with the required probability. Investigations with simply supported beams and two cars burning simultaneously showed the same results.

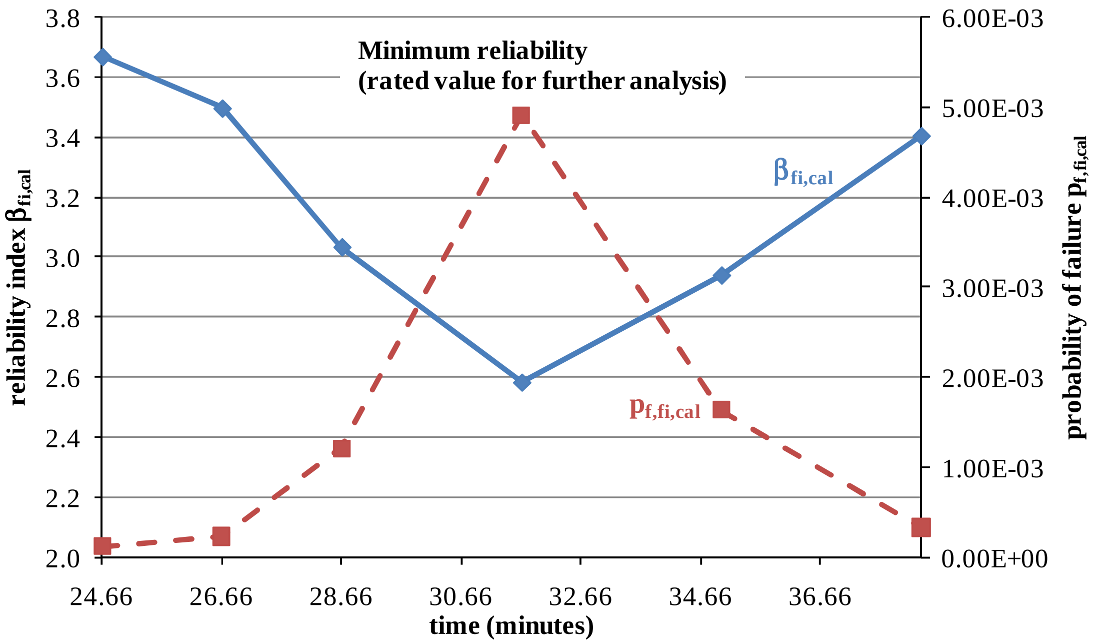

Figure 5 Calculated target conditional probability of failure $p_{f,fi,calc}$ (dashed) and the corresponding reliability index $\beta_{fi,cal}$ (solid) in the critical timeframe

Investigations concerning the sensitivity clearly demonstrated that the concrete compressive strength does not have a significant impact on the reliability development (see Figure 6). The same applies for the steel yield strength and the mechanical loads. The biggest influence could be determined from the rate of heat release (RHR) and the fire load. An interesting detail is the fact that the influence of RHR is decreasing with the time whereas the influence of the fire load increases. This complies of course with the physical phenomena.

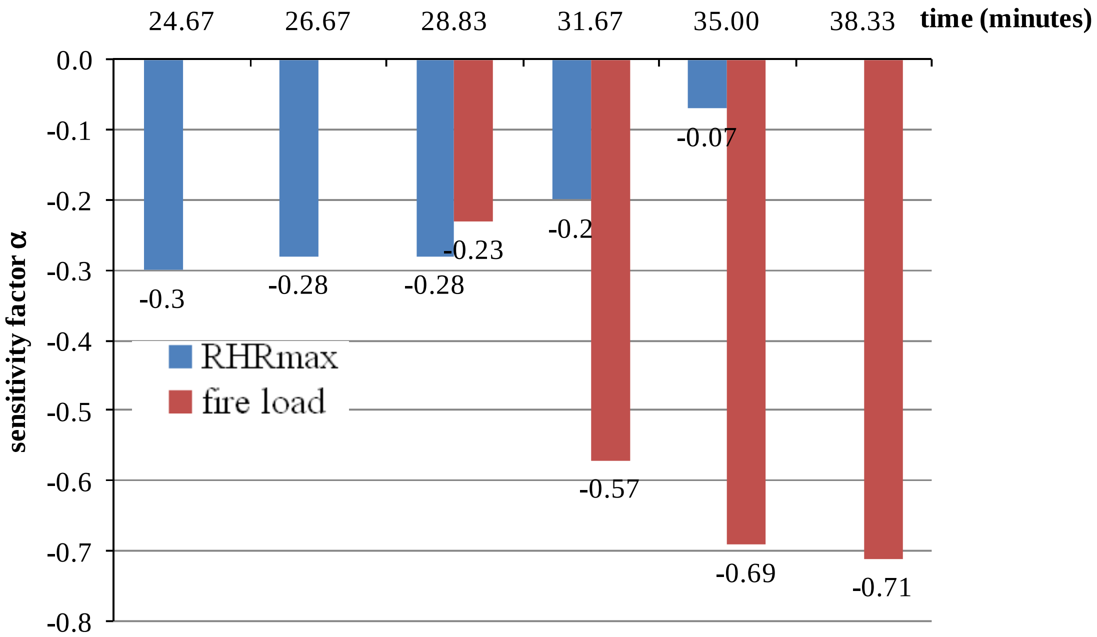

Figure 6 Development of the sensitivity factors versus time of fire exposure

In summary with the investigations on probabilistic basis it could be demonstrated that the calculated target conditional probabilities of failure $p_{f,fi,cal}$ actually are in the expected range. The most relevant parameters are those defining the fire: the RHR and the fire load. Most decisive for the results is the definition of the number of cars burning simultaneously. This, however, is a deterministic definition.

Proposal of a natural fire design model for open car parks and application

The prior investigations on probabilistic basis lead to the following proposal of a natural fire model for open car parks. The fire scenario is described by a local fire acc. to EC1-1-2 which is defined by design values of the RHR and the fire load. The appropriate safety factors can be derived from Equations (1) to (3). In the previous section Equations (2) and (3) have already been solved. The results are depicted in Table 1. Together with Figure 2 the safety factors can be determined in dependence of the safety index. The results are presented in Table 3.

Table 3: Partial safety factors for open car parks in dependence on the intervention time

	< 15 min	> 20 min
$\gamma_{fi,q}$	0.928	0.998 ≈ 1.0
$\gamma_{fi,\dot{Q}}$	0.947	0.999 ≈ 1.0

It becomes obvious that the safety factors are close the value 1.0. On the safe side the calculation of the design RHR and design fire load safety of 1.0 are taken into account. The characteristic values of the RHR as well as the fire load are derived from the mean values and the appropriate standard deviations to the 90%-fractile of the normal distribution which are given in Table 2:

$$RHR_d = RHR_k \cdot \gamma_{fi,\dot{Q}} \quad (5)$$

where

RHR_k is characteristic value of the heat release rate
= 5,000+ 1.28 · 500 = 5,640 kW/car

$\gamma_{fi,\dot{Q}}$ is the safety factor acc. to Table 3.

$$q_d = q_k \cdot \gamma_{fi,q} \quad (6)$$

where

q_k is characteristic value of the fire load
= 5,500+ 1.28 · 550 = 6,200 MJ/car

$\gamma_{fi,q}$ is the safety factor acc. to Table 3.

The course of RHR for two cars burning simultaneously and the appropriate gas temperatures are depicted in Figure 7.

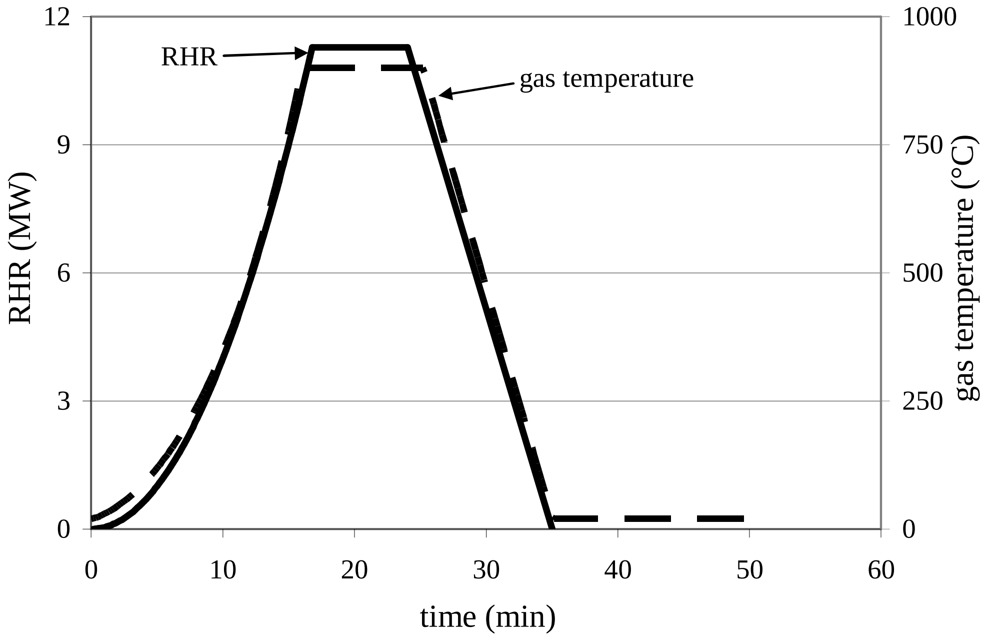

Figure 7 Rate of heat release and appropriate gas temperature versus time for a design fire scenario with two cars

The comparison to natural fire measured in open car park tests [8] (see. Figure 8) shows that the gas temperatures of the proposed design model satisfyingly cover the measured values.

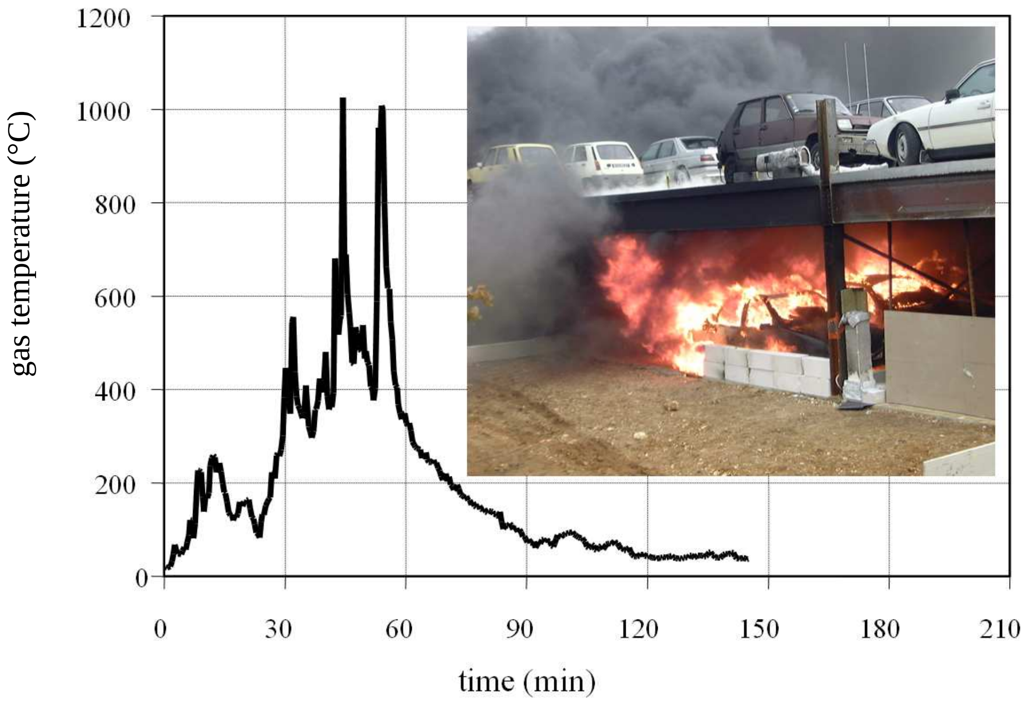

Figure 8 Measured gas temperatures versus time of an open car park test with three effected cars [8]

Subsequently the composite beam has been analysed numerically with the computer program BoFire in a thermal and mechanical analysis. The calculation proofed that the beam is able to resist the design fire acc. to Figure 7. For this reason is could be demonstrated that the proposed natural fire design model for open car parks leads to an assessment which also would be achieved if prescriptive German building regulations would have been applied.

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