Performance based design of office buildings using the equivalent time method

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ABSTRACT

This paper illustrates the background of the German code DASt-Guideline 019 [1], which is foreseen to regulate the fire safety of steel and composite members in office buildings. In the present, regulations of office buildings guarantee the fire safety, demanding the same general fire resistances as for residential buildings. However, the focus of the hereby used classification is on residential buildings and the resulting maximum requirements do not consider the specific conditions of a building or active fire fighting measures. The DASt-Guideline 019 provides rules, which allow a fire design considering the performance of the building. Hence it is possible to reduce the fire resistance without reducing the safety of the users.

INTRODUCTION

The authors were assigned by the German Committee for Steel Construction to work out the scientific background of a code, which enables a reduction of passive fire safety requirements. Research achievements should be made available for usual engineering. Easements of the fire protection requirements could abet steel construction. E.g., for structural members in open car parks no fire protection is demanded, with the effect that almost every new open car park in Germany is a steel construction.

Hence, a premise for the development of such a code was, that the object of interest was not regulated satisfactorily and that it facilitates the passive fire protection requirements without diminishing the safety of the users. For this purpose different methods to design fire safety requirements were assembled. The methods were examined in view of different utilisations, keeping in mind, that the aim was a reduction of passive fire safety requirements.

To fulfil this aim the risk and the response of a building to a fire has to be considered, the impact of the fire and the influence of active fire fighting measures.

The result of these considerations is the DASt-Guideline 019. The performance of the building is calculated via the equivalent time method. The main parameters governing a fire – fire load density, ventilation conditions and the thermal properties of the enclosure – are considered. Classified products, tested with standard fire curves, are linked by the equivalent time method to natural fires. Nevertheless it is possible to calculate the performance of structural members in a fire, using the "hot" Eurocodes [2]. Office buildings usually are designed by the same prescriptive rules as residential buildings by the actual German building code MBO [3], although they are considered safer and active fire fighting devices are not unusual. Office buildings are not regulated and the market segment for office buildings is interesting for the steel construction industry. Finally a mitigation of passive fire protection for office buildings was apparent.

COMPARISON OF FIRE RISKS IN DWELLINGS AND OFFICE BUILDINGS

The risk of fire death in residential buildings compared to office buildings is high. 80 % of the fatalities are caused by fires in residential buildings [4][5]. The reason is not only the greater built surface of residential buildings. The casualty rate per fire for residential buildings is higher

than for office buildings [5]. Risk to life data shows, that children under the age of 5 and senior citizens over 65 have the greatest risk of fire death [4][5]. A high percentage of the casualties in residential buildings are caused by burning beds or clothes. In contrast to persons in residential buildings, persons in office buildings are generally capable of acting, they alert a fire fast and they know the locality. Furthermore the fire occurrence and the fire load density in office buildings are lower than in residential buildings [5].

occupancy	fire occurrence per surface area of compartment and year $(1/m^2a)$	mean fire load density (MJ/m^2)
office buildings	$2 \cdot 10^{-6}$ to $4 \cdot 10^{-6}$	420
residential buildings	$4 \cdot 10^{-6}$ to $9 \cdot 10^{-6}$	780

Table 1: Fire occurrence and fire load density depending on the occupancy [5]

Especially the data in Table 1 justify a reduction of fire resistance requirements, since the fire load density decisively influences the exposure of the structure to a fire and the fire occurrence determinates the required safety level. Consequently in the DASt-Guideline 019 these parameters are included.

FIRE PROTECTION REQUIREMENTS

The safety level of the DASt-Guideline 019 is calibrated at the requirements for residential buildings. A calculation of the fire requirements with the methodology used in the DASt-Guideline 019, but parameters typical for residential buildings, result in the same requirements stated in the actual building code (MBO [3]).

The decision to calculate the impact of a fire with the equivalent time method was encouraged by the fact, that this method is already used to design the fire requirements in industrial buildings. The codes for industrial buildings were models for an effective fire safety design.

Hence, the essential definitions and requirements of the building code MBO adopted in the DASt-Guideline 019 are explained and a survey of the industrial building codes [7][8] is given.

Building code (MBO, 2002)

The German building code MBO is a recommended model regulation, which is not obligatory for all federal states. But most of the federal states follow these recommendations with differences in detail. The MBO defines amongst other things the fire requirements of usual buildings. So without further proof the fire safety concept of usual residential buildings and office buildings will be established conforming to the MBO.

Five building classes in dependency of the height of the upper floor are defined. In the DASt-Guideline 019 the last three building classes relevant for common office buildings are adopted. Fig. 1 shows the three building classes and the respective fire resistance requirements for structural members. The DASt-Guideline 019 does not refer to other regulations of the MBO, like the length of the escape routes, or the access possibilities to the building. These rules must be accomplished conforming to the MBO and are unaffected of the DASt-Guideline 019.
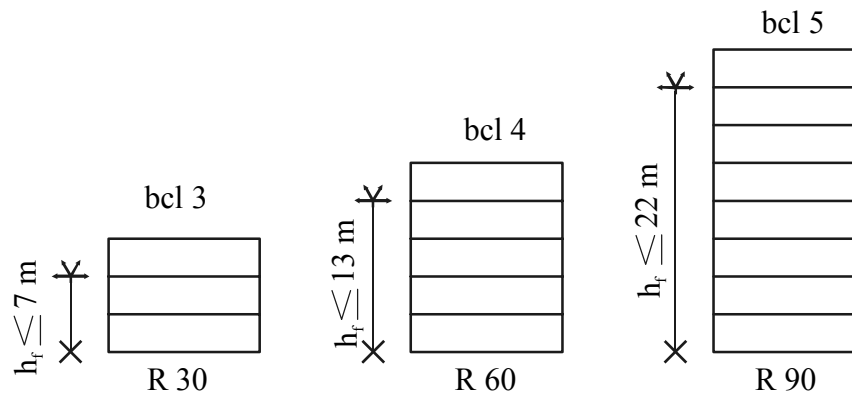
Fig. 1: Building classes (bcl) and required fire resistance of structural members [3].

The building classes obviously consider the possibilities of the fire brigade to rescue occupants. The height h_f of the buildings is correlated to the different types of fire ladders. Only an aerial ladder enables the second obligatory escape route of building class 5. This comparatively difficult evacuation implies severer fire resistance requirements for structural members. The structural fire safety requirements assigned to the building classes account for the possibilities of the fire brigade to rescue occupants and to extinguish the fire.

Industrial buildings

The regulatory frame for fire safety design of industrial buildings is given by two codes: The German standard DIN 18230-1 (1998) [8] and the German Guideline for Industrial Buildings [7]. In the Guideline for Industrial Buildings, three levels of fire safety design are provided. The first level comprises simple design tables, which contain the maximum size of the compartment in dependency of the number of storeys, the fire safety measures and the fire resistance class of the structural members. The second level includes the calculation of the equivalent time. The evaluation method with its safety factors is described in DIN 18230-1. On this level the determination of fire load densities is necessary, because the variation of fire load densities in industrial buildings does not permit a statistical evaluation. Only experts working as fire consultants can accomplish this task in co-ordination with the authority having jurisdiction. The third level sets basic conditions for experts using fire engineering methods.

The safety concept of the DASt-Guideline 019 is basically the same. The probabilistic safety concept enables the consideration of safety measures like fire alarm systems, plant fire brigades, sprinklers or the number of storeys. The procedure is similar to the one presented in this paper.

EQUIVALENT TIME METHOD

The equivalent time is the link between the temperatures attained in a natural fire and the temperatures in ISO fire. It is the time a steel casting element (400 × 400 × 150 mm) subjected to the ISO fire curve heats up to the same temperature as in a natural fire. Natural fire tests with wood cribs were performed to establish a basis. As a result the dependency of the equivalent time to the fire load density and the thermal properties of the enclosure of the fire compartment could be determined. With numerical calculations these results were extrapolated to bigger compartments, resulting in a ventilation factor according to Eqn. (2). The temperature of the casting element is measured in 50 mm depth. The casting element was chosen in a way, that the temperatures calculated by the equivalent time method yield good results for the reinforcement in concrete structures or insulated steel members [9]. These temperatures are good estimates for the fire resistance of concrete beams or insulated steel

beams. Therefore a classification in fire resistance classes is possible. The performance of any component in a fire is comparable with ISO fire testing. Hence, by comparing fire resistance classes an extrapolation of the results of the equivalent time method to other materials or components is possible. The equivalent time method is independent of the material and it is possible to profit of the vast experience of ISO fire testing.

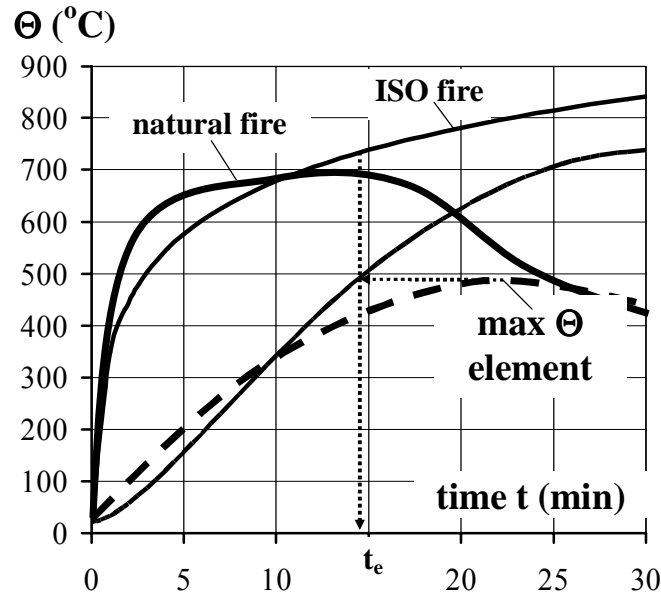The definition of the equivalent time t_e is illustrated in Fig. 2.

Fig. 2: Equivalent time of fire exposure t_e

Definitions

The characteristic value of the equivalent time is given by Eqn. (1),

$$t_e = q_{f,k} \cdot k_b \cdot w_f \quad (min) \tag{1}$$

with:

$q_{f,k}$ fire load density per unit floor area (MJ / m^2)
k_b conversion factor (min · m² / MJ) depending on the thermal properties of the enclosure
w_f ventilation factor (-)

$$w_f = \left(\frac{6}{H}\right)^{0.3}\left[\frac{0.62 + 90(0.4 - \alpha_v)^4}{1 + b_v\alpha_h}\right] \geq 0.5 \tag{2}$$

where

α_v is the area of vertical openings in the façade related to the floor area of the compartment (-)
α_h is the area of horizontal openings in the roof related to the floor area (-),
H is the height of the fire compartment (m) and
$b_v = 12.5\left(1 + 10\,\alpha_v - \alpha_v^2\right) \geq 10.0$

Where no detail assessment of the thermal properties is made the conversion factor k_b may be taken as 0.07 min · m² / MJ [1].

Fire load density

The fire load density is one of the main parameters governing a fire. The determination of the fire load densities for industrial buildings requires experts. This is the cause for additional costs and planning insecurities. This procedure would not be feasible for office buildings. But in contrast to industrial buildings the utilisation and the arrangement of office buildings always resembles, so that a statistical evaluation is possible. This great advantage allows establishing fixed values for the fire load density. As an overview of published statistical data in dependency of the utilisation showed [5][10][11][12], three main categories given in Table 2 for fire load densities in office buildings could be established. The data of the literature did not differ considerably.

Table 2 comprises the fire load densities relevant for office buildings as in [5] and used in the DASt-Guideline 019.

categories of fire load densities	90 % fractile $q_{f,k}$ (MJ/m²)	80 % fractile (MJ/m²)	mean (MJ/m²)
public space	<u>162</u>	122	101
office, standard	<u>576</u>	511	421
library	<u>2088</u>	1825	1501

Table 2: Fire load densities for different kinds of utilisation areas in office buildings [5]

Three main utilisation areas are defined in the DASt-Guideline 019. The average fire load density of office buildings is the one defined in Table 2 as "office, standard" and includes office rooms, technical rooms, conference rooms and corridors. The highest fire load densities are in libraries and the lowest in public spaces, like lobbies or arrival halls. A separate compartment is necessary, if the fire load density differs more than 50 % from the average, as it is in libraries. The fire requirements for a public space could be reduced if it is designed as a separate compartment. The architect has to arrange the utilisation within the building. This should not be a problem, since the structural design also affords the determination of the utilisation within a building. E.g. for libraries a live load of 5 kN/m² is demanded, whilst for the remaining office area 2 kN/m² is sufficient.

SAFETY CONCEPT

The performance of the building is described by the equivalent time as an action and the ISO fire resistance time as a resistance. Both quantities are random variables and a sufficient safety margin is achieved by safety factors γ. The necessary safety margin accounts for the possibilities of the fire brigade to rescue occupants in dependency of the building class. Furthermore active fire fighting measures are considered. Safety classes are defined, containing an additional factor α_L, which reduces the required fire resistance time. The required fire resistance time is calculated with Eqn. (3) and corrected with factors accounting for the building class.

$$\text{req } t_F = t_e \cdot \gamma \cdot \alpha_L \quad (\text{min}) \tag{3}$$

γ Safety factor in dependency of the compartment area (s. Table 6)

α_L additional factor to consider active fire fighting measures (s. Table 8)

The calculated, required fire resistance time is used to determine the fire resistance class of structural members according to Table 9.

Target failure probability

In any regulation a safety margin is implemented either directly as a failure or target probability or indirectly in specific requirements. Mostly these requirements are historic developments, based on experience. The DASt-Guideline 019 is based on a probabilistic concept, so that the determination of the safety level is necessary to provide safety factors.

The target failure probability is determined by the required fire resistance classes of the MBO (s. Fig. 1). Starting point is the failure probability $p_t = 10^{-5}$ per year (1/a). This value corresponds to the personal fire fatality risk identified from international statistics and is the target failure probability for load-bearing structures in fire and normal risks in Germany. Other publications derive a similar target probability [5][11]. A very interesting proposal is in [5], where the target failure probability is differentiated in dependency of the evacuation possibilities:

Normal evacuation $p_t = 1.3 \cdot 10^{-4}$ 1/a

Difficult evacuation $p_t = 1.3 \cdot 10^{-5}$ 1/a (e.g. hospitals)

No evacuation $p_t = 1.3 \cdot 10^{-6}$ 1/a

This proposal is similar to the target failure probabilities used in the DASt-Guideline 019. If the target failure probability $p_t = 10^{-5}$ 1/a is applied for usual residential buildings of building class 5 (s. Fig. 1), where the fire safety requirement is R 90, then the target failure probabilities for the building classes 3 and 4, where the fire safety requirement is R 30 and R 60 must be greater. A valuation using parameters common for residential buildings and applying the safety concept resulted in the target failure probabilities given in Table 3:

building class	target failure probability p_t
5	$1 \cdot 10^{-5}$
4	$10 \cdot 10^{-5}$
3	$20 \cdot 10^{-5}$

Table 3: Target reliability of structural members in dependency of the building class (reference period 1 year)

It is important to notify, that the greater target failure probabilities of building classes 3 and 4 consider the better possibilities of the fire brigade to rescue the occupants and to extinguish the fire, as well as the better salvation possibilities of the occupants themselves.

Conditional failure probability

A fire damage is a rare event and treated as an accidental load. Hence it is sufficient to design the fire requirements of structural members for the conditional probability p_f to fail in a fire [13]. This way the risk of ignition is considered and the effects of active fire fighting measures like sprinklers or fire alarm systems. The conditional probability is calculated with Eqn. (4):

$$p_f = p_t / p_{fi} \qquad\qquad (4)$$

$$p_{fi} = p_1 \cdot p_2 \cdot p_3 \tag{5}$$

p_{fi} Probability of a dangerous fire

$p_1 = \lambda \cdot A$ Probability of ignition:

         $\lambda = 5 \cdot 10^{-6}$ 1 / m² a (see Table 1)

         A   Area of the fire compartment (m²)

$p_2 = 0.1$ Probability that the fire brigade fails

p_3 Probability that active fire fighting measures fail (see Table 4)

safety category	active fire fighting measures	failure probability p_3
K1	none	$p_3 = 1$
K2	fire alarm system	$p_3 = 0.5$
K3	fire alarm system and plant fire brigade	$p_3 = 0.25$
K4a	sprinkler system	$p_3 = 0.01$
K4b	sprinkler and fire alarm system	$p_3 = 0.005$

Table 4: Failure probability p_3 and safety categories according to the DASt-Guideline 019

Safety factors γ

The limit state function to determine the safety factors is given by Eqn. (6) and the ultimate state by Eqn. (7). Failure occurs, when the equivalent time t_e is greater than the fire resistance time t_f.

$$g(X) = t_f - t_e \tag{6}$$

$$Z = t_f / t_e = 1.0 \tag{7}$$

A measure of the distance between both probability densities t_e and t_f, is the failure probability p_f or the reliability index β_f given by Eqn. (8)

$$\beta_f = \Phi^{-1}(1-p_f) \tag{8}$$

For both probability density functions t_e and t_f a lognormal distribution is assumed [13].

	COV	nominal value	fractile value
fire resistance time	0.25	10 %	-1.282
equivalent time	0.45	90 %	+1.282

Table 5: Variables of the lognormal variates t_f and t_e to calculate the safety factors γ

Starting from Eqn. (4) and (8) for the safety category K1 and the target failure probability of building class 5 reliability indices in dependency of the compartment area are evaluated. Then, the partial safety coefficients based on Eqn. (7) are calculated using the parameters for lognormal density distributions of Table 5. Table 6 shows the resulting safety factors used in

the DASt-Guideline 019 [1]. A detailed elaboration of the safety factors and further references are presented in [14].

A (m²)	β_f	γ_e	γ_F	$\gamma_{calc}=\gamma_e \cdot \gamma_F$	γ
500	1.75	1.11	0.90	1.00	1.00
1000	2.05	1.24	0.84	1.16	1.15
1500	2.22	1.32	0.96	1.26	1.25
3000	2.48	1.45	0.99	1.43	1.45
5000	2.65	1.55	1.01	1.56	1.55

Table 6: Reliability index, partial safety factors and global safety factor used in DASt-Guideline 019 in dependency of the compartment area

Coefficients for building class 3 and 4

The same procedure is conceivable for building class 3 and 4, using the target failure probabilities of table 2. However, it is possible to specify correction factors, which solely depend of the building class. For this matter coefficients for building class 3 and 4 are calculated, based on the average compartment area of the building class and its respective target failure probability. The ratio of these safety factors with the safety factor corresponding to the building class 5 is the sought-one. The average area of the fire compartment for building classes 3 to 5 was evaluated from the statistical data of completed buildings in Lower Saxony (1983 to 2000).

building class	average area A of building class 3 and 4 [m²]	$\gamma_{3,4}$ building class 3,4	γ building class 5	building class coefficient
3	750	0.40	1.09	0.4
4	3500	0.93	1.48	0.6

Table 7: Coefficients for Building class 3 and 4

Additional factor α_L for Active Fire fighting Measures

The method presented here is applied also to calculate the safety coefficients α_L, which reduce the required fire resistance time. In the DASt-Guideline 019 safety categories are defined in dependency of the fire fighting infrastructure. For each of these categories the failure probabilities given in Table 4 are assigned. For an average compartment area of $\overline{A} = 1500$ m² (for all building classes) safety coefficients γ_{p_3} are calculated, using the reliability index conforming to Eqn. (4) and (8). The ratios of these coefficients with the one for the safety category 1 are the safety coefficients α_L (9). The results of Eqn. (9) are presented in Table 8.

$$\alpha_L = \gamma_{p_3} / \gamma \qquad (9)$$

safety category	K1	K2	K3	K4a	K4b
α_L [-]	1.0	0.9	0.8	0.4	0.3

Table 8: Additional factor α_L for the safety categories defined in Table 4.

RESULTS

The required fire resistance req t_F (s. Eqn. (3)) is used to define fire resistance classes according to Table 9 for structural elements.

required time of fire resistance req t_F	required fire resistance
0 < req t_F ≤ 15 min	no requirements
15 min < req t_F ≤ 30 min	R 30
30 min < req t_F ≤ 60 min	R 60
60 min < req t_F	R 90

Table 9: Specification of the required fire resistance class for structural elements

Fig. 3 shows the results for the building classes 3, 4 and 5 (s. Fig. 1.) according to the presented method: The minimum fire protection requirements with its respective maximum compartment area in dependency of the safety categories (s. Table 4). The value of the ventilation factor is assumed to be w = 1.4. This is a typical value for office buildings. As well as k_b = 0.07 min · m² / MJ to consider the thermal properties of the compartment enclosure, which varies between $0.04 \leq k_b \leq 0.07$.
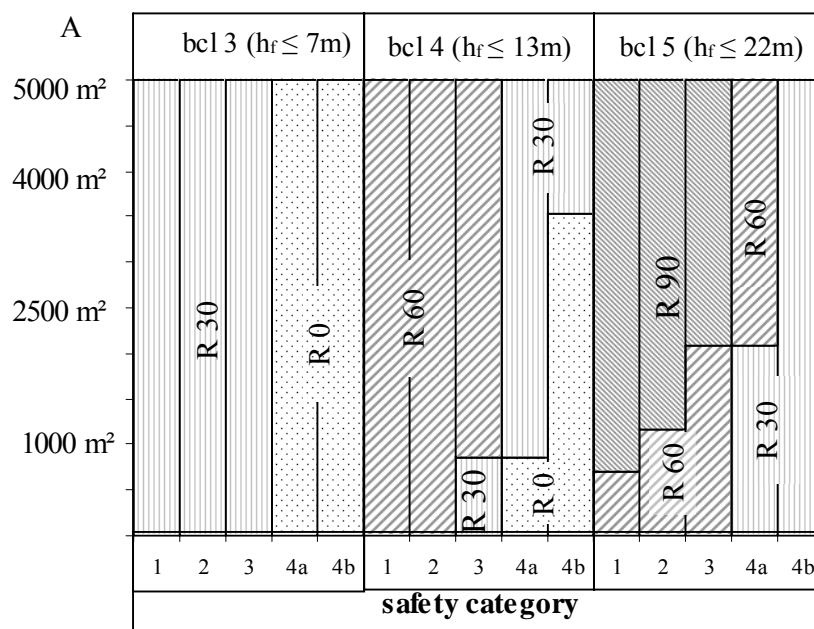

Fig. 3: Fire requirements for structural elements in dependency of the compartment area A, the safety category and the building class, for $q_{f,k}$ = 576 MJ/m²; w = 1.4; c = 0.07 min · m² / MJ.

Obviously the main effect on the required fire resistance class is achieved by the sprinklers, defined in the categories K4a and K4b: The reduction of at least one fire resistance class is possible independently of the building class installing sprinklers. A moderate reduction is also identifiable for small compartment areas of building classes 4 and 5.

SUMMARY

The paper explains the motives to issue the DASt-Guideline 019, which is focused on office buildings and based on the equivalent time in connection with a probabilistic concept. The background of the equivalent time and the probabilistic concept are presented. Finally the results achieved by the application of the DASt-Guideline 019 are illustrated.

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