CHANCES AND LIMITS OF THE TIME-EQUIVALENCE-METHOD IN STRUCTURAL FIRE DESIGN

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ABSTRACT

This paper deals with the application of the time-equivalence-method in fire safety design. The presentation of the German regulations for industrial buildings identifies the advantages of this simplified and easy-to-use design method. Active fire protection measures, such as automatic fire alarm or sprinkler systems may be taken into account when the required fire resistance time of structural members is determined. Thus, unprotected steel structures may be used in industrial buildings under certain conditions. In order to check the range of validity, a number of calculations have been carried out using the time-equivalence-method and alternative methods. The research concerns unprotected and protected steel members. The results demonstrate that the calculation of the maximum steel temperature on the basis of the equivalent time of fire duration may only be recommended for protected steel members. Nevertheless the time-equivalence-method embedded in a probabilistic safety concept could be excellently suitable to access the required fire resistance of structural members allowing compensation of passive fire protection by active protection measures.

KEYWORDS

Structural fire design, steel members, time-equivalence-method, industrial buildings

BASIC IDEA OF THE TIME-EQUIVALENCE-METHOD

The time-equivalence-method creates a relation between the effects of heating in structural members caused by natural fires and those caused by the ISO fire curve. Concerning steel structures the equivalent time of fire exposure defines that time of ISO fire exposure, which causes the same maximum steel temperature as the corresponding natural fire. The definition of the equivalent time of fire exposure is illustrated in Figure 1.

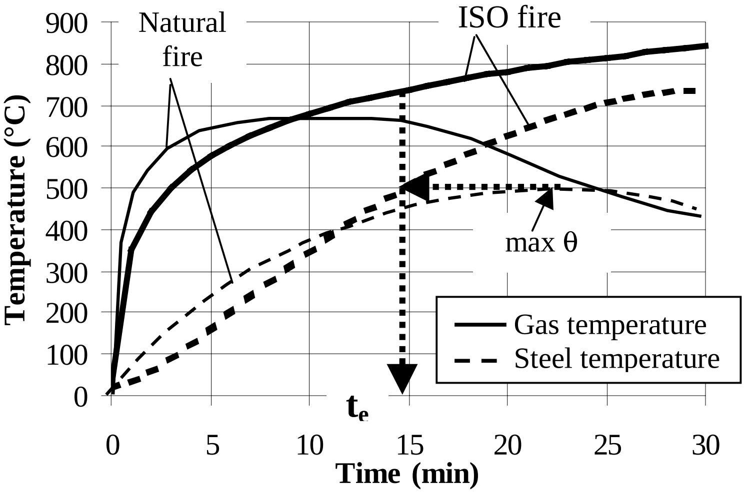


Figure 1: Equivalent time of fire exposure t_e

GERMAN FIRE DESIGN CONCEPT FOR INDUSTRIAL BUILDINGS

The German fire design codes for industrial buildings are based on the time-equivalence-method. This method is embedded in a probabilistic safety concept taking into account the actual fire load, the actual number of storeys, the relevant areas for heat exhaust and different additional fire safety measures like fire alarms systems, plant fire brigades or sprinklers. The regulatory frame is given by two codes: the German standard DIN 18230-1 (1998) and the German Guideline for Industrial Buildings (Guideline for Structural Fire Protection of Industrial Buildings (2000)). The contents of these codes are summarised hereafter.

In DIN 18230, an analytical method is provided for the evaluation of the required equivalent time of fire exposure. This value leads to the determination of a so-called fire protection class, which is the link to the Guideline for Industrial Buildings. In particular, the required fire resistance class of structural members and the maximum size of compartements are specified in this code. Figure 2 gives an overview on the contents of the fire design regulations for industrial buildings.

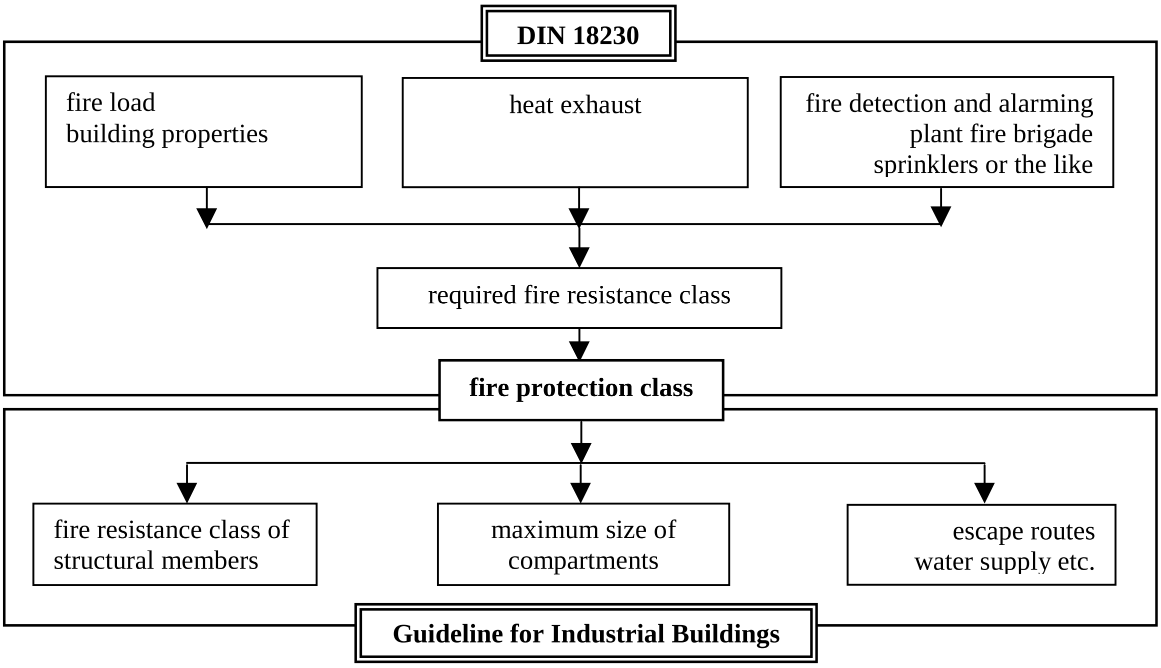


Figure 2: Connection between DIN 18230 and the Guideline for Industrial Buildings

In the Guideline for Industrial Buildings, three fire safety design approaches are provided on three different levels. 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 category and the fire resistance class of the structural members. The fire safety category is a special feature taking into account measures like fire alarms systems, plant fire brigades or sprinklers; it is explained in Table 1. This level needs no explicit evaluation of the required equivalent time, which is included in the table. Thus, no determination of the actual fire loads is needed. According to Table 1, unprotected steel structures may be used for single storey industrial buildings up to maximum area of 1800 m^2 without special measures for fire alarm or fire fighting. If an automatic sprinkler system is installed, the maximum area may reach 10000 m^2.

On the second level, the evaluation method given in DIN 18230 is used on the basis of actual fire loads in the building. This method for calculating the equivalent time of fire exposure is equal to the method given in Annex E of EC1-2-2 (ENV 1991-2-2 (1995)). The characteristic value of the equivalent time of fire exposure is given by Eqn. 1

TABLE 1

MAXIMUM AREA (m^2) OF FIRE COMPARTMENT IN SINGLE STOREY INDUSTRIAL BUILDINGS

Safety category		**Fire Resistance Class of Load Bearing Members**	
		R 0	**R 30**
K 1	without special measures for fire alarm and fire fighting	1800*)	3000
K 2	with automatic fire alarm system	2700*)	4500
K 3	with automatic fire alarm system and plant fire brigade	3200 to 4500*)	5400 to 7500
K 4	With sprinklers or the like	10000	10000
*) minimum area of heat exhaust openings in the roof 5 %, maximum width of building 40 m			

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

with

$q_{f,k}$ $(\mathrm{MJ/m^2})$ fire load density per unit floor area

k_b $(\mathrm{min \cdot m^2/MJ})$ conversion factor

w_f $(-)$ ventilation factor

The actual design value of the fire load density normally has to be estimated by experts working as fire safety consultants in co-ordination with the authority having jurisdiction. The conversion factor takes into account the thermal properties of the enclosure of the fire compartment. It ranges between $0.04 \le k_b \le 0.07\ (\mathrm{min \cdot m^2/MJ})$. The factor k_b depends on the thermal property $b = \sqrt{\rho \cdot c \cdot \lambda}$ $(\mathrm{J/(m^2 s^{1/2} K)})$ of the enclosure, including unit mass, specific heat and thermal conductivity of the enclosure material. The ventilation factor takes into account the ventilation conditions of the compartment, which mainly depend on vertical and horizontal openings. It ranges between 0.35 and 3.0.

The equivalent time of fire exposure t_e is embedded in a probabilistic safety concept. Multiplication of t_e with two factors gives the required time of fire resistance req t_F (see Eqn. 2). The required fire resistance class of the structural elements is specified in dependency of the required time of fire resistance in Table 2.

$$\mathrm{req}\, t_F = t_{e,k} \cdot \gamma \cdot \alpha_L \quad \text{(min)} \tag{2}$$

with γ $(-)$ $(1.0 \le \gamma \le 1.6)$ safety factor depending on the floor area of the fire compartment and the number of storeys

α_L $(-)$ $(0.342 \le \alpha_L \le 1.0)$ additional factor concerning active measures of fire safety such as automatic fire alarm or sprinkler systems.

TABLE 2

SPECIFICATION OF THE REQUIRED FIRE RESISTANCE CLASS

Required Time of Fire Resistance (min)	Required Fire Resistance Class for Structural Elements
$0 < \mathrm{req}\ t_F \le 15$	no requirements
$15 < \mathrm{req}\ t_F \le 30$	R 30
$30 < \mathrm{req}\ t_F \le 60$	R 60
$60 < \mathrm{req}\ t_F$	R 90

It should be emphasised that no fire resistance requirements must be met for structural members if the required time of fire resistance is less than 15 minutes. That means that unprotected steel construction may be used.

The level three design approach of the Guideline for Industrial Buildings may be identified as the performance-based option of the code. Fire engineering methods may be applied for evaluating the effects of fire in the building as well as the heating and the load bearing behaviour of the structure under elevated temperatures.

APPLICABILITY OF THE EQUIVALENT-TIME-METHOD

Objective

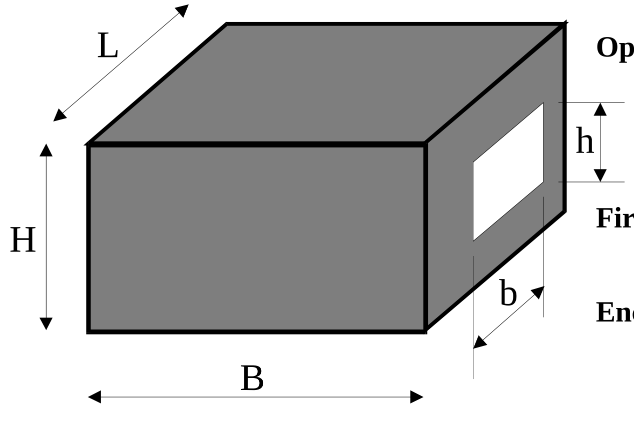
In the context of the structural fire design for steel structures ruled by EC3-1-2 (ENV 1993-1-2 (1995)) the question arises, whether the time-equivalence-method is a suitable method for determining the maximum steel temperatures under natural fires. This question defines the objective of the investigations presented hereafter. A positive result would have two decisive advantages for the simplification of assessment methods. First, the development of gas-temperatures in the compartment in natural fires could be taken into account using a very simple approach related to the ISO-fire curve. Second, the recognised solutions for the heating of unprotected and protected steel sections given in EC3-1-2 may be applied.

Method of Investigation and Parameters of the Study

To check to applicability of the equivalent-time-method, maximum steel temperatures calculated according to three different approaches for natural-fire-curves are compared to each other. The three methods of taking natural-fire-curves into consideration are:

• **EC1-2-2 Annex E**	The natural-fire-curve is substituted by ISO-fire curve with an equivalent time t_e according to Eqn. (1).
• **EC1-2-2 Annex B**	The natural-fire-curve is given by a parametric gas-temperature-time-curve according to Annex B of EC1-2-2.
• **OZone**	The natural-fire-curve is calculated by the computer model OZone, which is based on a one-zone heat-balance-method. See Cadorin, J. f. and Franssen, J. M. (2000).

Applying the first method (EC1-2-2 Annex E), the equivalent time t_e is given directly. In case of the other two methods the equivalent time t_e is determined following the procedure given in Figure 1.



Opening factor:

$$O = A_v \cdot \sqrt{h} / A_t$$

A_v : area of vertical openings

A_t : total area of enclosure

Fire load density per unit floor area:

$Q_{f,k}$ = 500 MJ/m² (Office)

Enclosure of fire compartment:

concrete

$$b = 1918\ J/(m^2 \cdot s^{0,5} \cdot K)$$

L / B / H = 5 / 5 / 2.5 [m]

Figure 3: Properties of fire compartment (basic scenario)

Fig. 3 shows the basic properties of the fire compartment chosen for this study. For the steel element exposed to natural-fire-curves a section factor of $A_m/V = 150\ m^{-1}$ has been chosen. Parameters varied in this study are the

- opening factor O ranging between 0.02 and 0.20 $m^{0.5}$
- type of structural fire protection:
  unprotected and box-protection (R 30) comprising a 12.5 mm gypsum board.

Results and Discussion

As an example of the temperature development of an unprotected steel section, Figure 4 shows the curves for the three methods of taking natural-fire-curves into account. In this example the opening factor was chosen to $O = 0.05\ m^{0.5}$. For this scenario the equivalent time t_e has been calculated to 31 min according to Eqn. 1. The main difference between the ISO-fire-heating and the temperature-time-curves calculated for real natural-fire-curves is that there is no cooling phase in the ISO-curve. The steel temperatures caused by the ISO-fire-curve are higher than those according to OZone and EC1-2-2 Annex B. The steel temperature-time-curves according to EC1-2-2 Annex B and OZone are similar but not congruent although they are both natural-fire-curves according to the same scenario. In particular, the maximum steel temperature of the Ozone calculation is higher in this example.

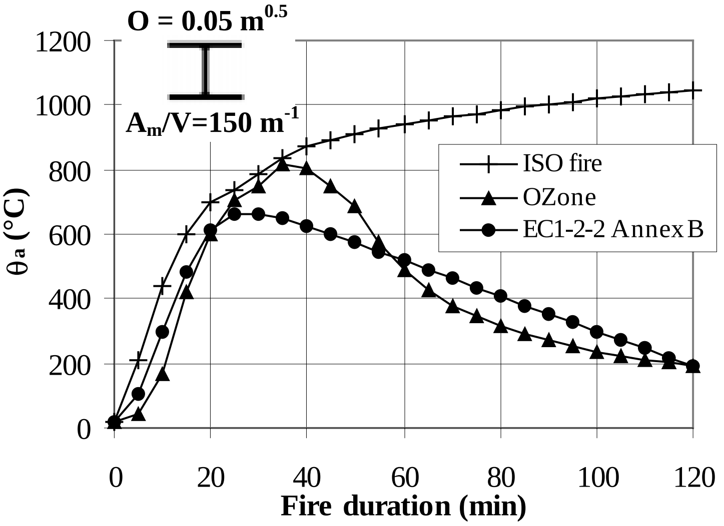


Figure 4: Temperature-time-curves of unprotected steel sections for different assumptions concerning the gas temperature

The maximum steel temperatures for a variation of the opening factor in the basic scenario are shown in Figure 5. The corresponding equivalent times of fire exposure can be taken from Figure 6. For instance the maximum steel temperature due to the OZone model for the opening factor $O = 0.05\ m^{0.5}$ can be found as 820°C in Figure 5. The respective equivalent time of fire exposure can be seen in Figure 6 as 33 minutes. In addition to the maximum steel temperatures for OZone and EC1-2-2 Annex B the recalculated maximum steel temperatures for the analytical method of EC1-2-2 Annex E are shown in Figure 5. These temperatures are calculated by inverting the method illustrated in Figure 1. The analytical method of EC1-2-2 Annex E is limited to maximum vertical openings of 25 % of the compartment's floor area. For the basic scenario this limit is reached at an opening factor of $O = 0.1\ m^{0.5}$. Nevertheless the results for opening factors higher than 0.1 $m^{0.5}$ are also presented in order to compare the shape of the curves. There are noticeable differences between the maximum steel temperatures especially for small opening factors. For an opening factor of 0.02 m^{-1}, the maximum steel temperatures vary between 510°C (EC1-2-2 Annex B) and 920°C (EC1-2-2 Annex E). For increasing opening factors between 0.02 and 0.08 $m^{0.5}$, the curve of Annex B shows an increasing trend while the maximum steel temperatures according to Annex E in general decrease. The maximum steel temperatures of the OZone model show an increasing trend between the opening factors 0.02 and 0.05 $m^{0.5}$ and for higher opening factors, they decrease continuously.

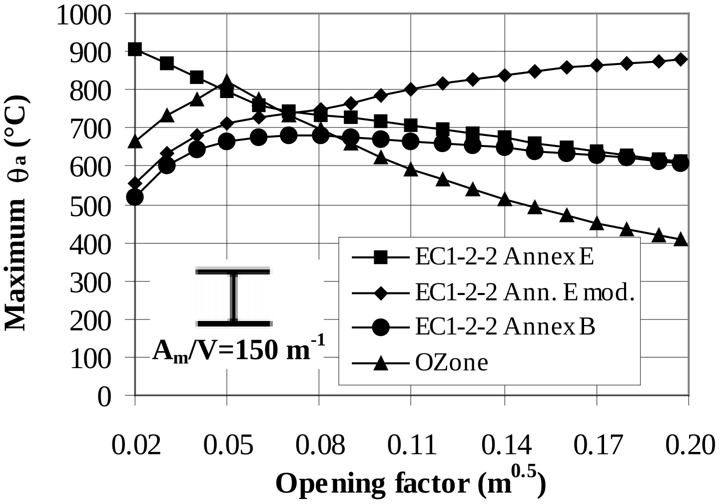


Figure 5: Maximum temperatures of unprotected member depending on the opening factor (basic scenario)

The respective curves for the equivalent time of fire duration (see Figure 6) show the same characteristics as the curves of the maximum steel temperatures. A proposal to fit the trend of the curve of Annex E to that of Annex B was made by Schleich, J. B. (1996). Therefore the equivalent time of fire duration is multiplied with 13,7×O (O = opening factor). The results are continually increasing curves for max θ_a and t_e identified by “EC1-2-2 Ann. E mod.” (see Figure 5 and 6).

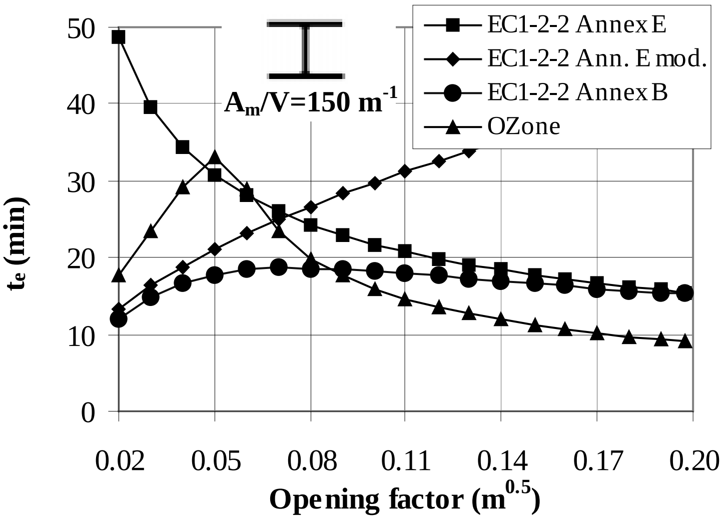


Figure 6: Equivalent time of fire exposure of unprotected member depending on the opening factor (basic scenario)

It can be stated that for unprotected members concerning the different methods, the resulting equivalent times of fire duration are very different. Concerning the described results, the applicability of the time-equivalence-method on unprotected steel members located in small fire compartments must be challenged.

In the following the results for a protected member are presented. The protected steel section features a box protection with gypsum boards. The properties of the board material are: unit mass $\rho_p = 945\,\mathrm{kg/m^2}$, thermal conductivity $\lambda_p = 0.20\,\mathrm{W/(m \cdot K)}$ and specific heat $c_p = 1700\,\mathrm{J/kg \cdot K}$.

Figure 7 shows the maximum steel temperatures of the protected member. The corresponding equivalent times of fire exposure are shown in Figure 8. The differences between the maximum steel temperatures of the different curves are not higher than 100°C for any opening factor. In general the OZone computer model produces the highest maximum steel temperatures and the method of EC1-2-2 Annex E the lowest. The curve of EC1-2-2 Annex B ranges between them except for very small opening factors (O = 0.02 $m^{0.5}$). All curves show a decreasing trend for increasing opening factors and they are developing nearly parallel to each other.

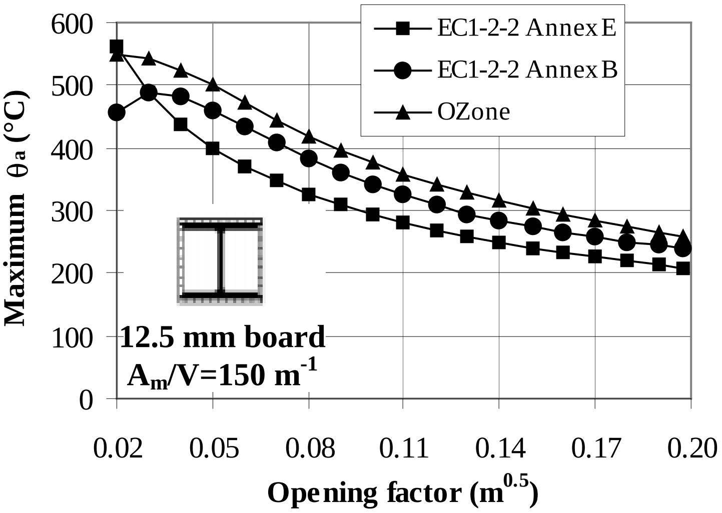


Figure 7: Maximum temperatures of protected member depending on the opening factor (basic scenario)

Concerning the corresponding equivalent times of fire exposure, the curves show the same characteristics as the temperature curves (see Figure 8). The maximum difference between the t_e-curves is about 14 minutes for a very small opening factor of O = 0.02 $m^{0.5}$.

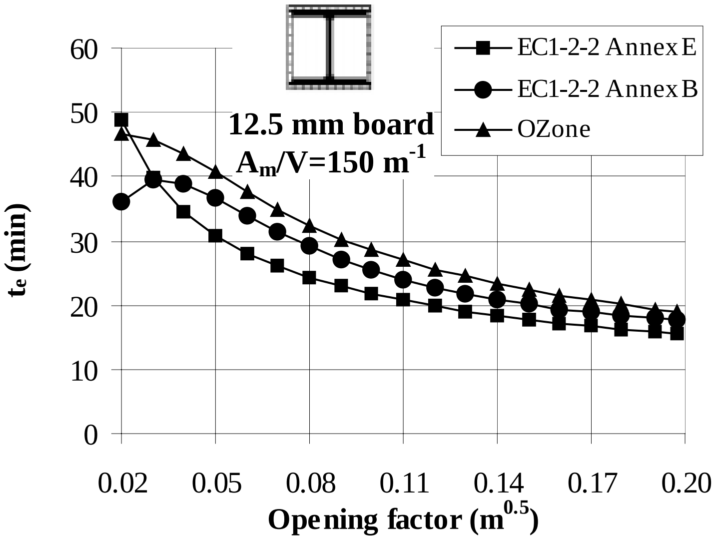


Figure 8: Equivalent time of fire exposure of protected member depending on the opening factor (basic scenario)

It can be assumed that for protected steel members the time-equivalence-method produces realistic results concerning the maximum steel temperatures.

CONCLUSION

This paper deals with the presentation of the German fire safety design regulations for industrial buildings based on the time-equivalence-method. Active fire protection measures, such as automatic fire alarm or sprinkler systems may be taken into account when the required fire resistance time of structural members is determined. Thus, unprotected steel structures may be used in industrial buildings under certain conditions. In order to check the range of validity, a number of calculations have been carried out using the time-equivalence-method and alternative methods. The research concerns unprotected and protected steel members. The results demonstrate that the calculation of the maximum steel temperature on the basis of the equivalent time of fire duration may only be recommended for protected steel members. For unprotected steel elements the results are too unfavourable. Nevertheless it should be tried to transfer the time-equivalence-method to other types of buildings and use. For this purpose the method has to be embedded in a probabilistic safety concept allowing compensation of passive fire protection by active protection measures.

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