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A Differentiated Approach to Structural Fire Engineering Design

Une méthode différenciée pour la détermination de la sécurité au feu des éléments de structure

Ein differenziertes Verfahren für die brandtechnische Dimensionierung von Baukonstruktionen

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A development of analytical design procedures, based on differentiated functional requirements, within different fields of the overall fire safety concept is an important task of the future fire research. Such procedures, successively replacing the present, internationally prevalent, schematic design methods, are necessary for getting an improved economy and for enabling more well-defined fire safety analyses. A derivation of such analytical design systems is also in agreement with the present trend of development of the building codes and regulations in many countries towards an increased extent of functionally based requirements and performance criteria.

For fire exposed load-bearing structures and partitions, an essential step in the direction of the described development was taken in the Swedish Standard Specifications of 1967 by introducing different alternatives of structural fire engineering design, leading to a different degree of accuracy and a different amount of engineering design work. This differentiated view is underlined further in the new edition of the standard specifications, in force from 1976.

A differentiated fire engineering design of load-bearing structures, as approved in the Swedish Standard Specifications, comprises a thorough determination of [1, 2, 3, 4, 5, 6, 7]
(a) the fire load characteristics,
(b) the gastemperature-time curve of the fire compartment as a function of the fire load density, the ventilation characteristics of the fire compartment, and the thermal properties of the structures enclosing the fire compartment,
(c) the temperature-time fields, and
(d) the structural behaviour and minimum load-bearing capacity of the fire exposed structure for a complete process of fire development.

The components of the design system as well as the appurtenant functional requirements are summarized in Fig. 1 for interior load-bearing structures. The survey covers the general case of application with additional requirement on reserviceability of the structure after a fire exposure.

As concerns the fire exposure characteristics, the Swedish Standard Specifications generally permit a structural fire engineering design on the basis of a gastemperature-time curve, calculated in each individual case from the heat and mass balance equations of the fire compartment with regard taken to the combustion characteristics of the fire load, the ventilation of the fire compartment, and the thermal properties of the enclosing structures of the fire compartment.

As a provisional solution, the structural fire engineering design may be based on differentiated gastemperature-time curves of the complete process of fire development, specified in the code. These fire exposure curves, exemplified in Fig. 2, are approximate curves, generally determined on the assumption of ventilation controlled compartment fires [8, 9, 10]. One principle reason for choosing this assumption as a general basis in this connection is dictated by the great difficulty in finding representative values of the free surface area and the

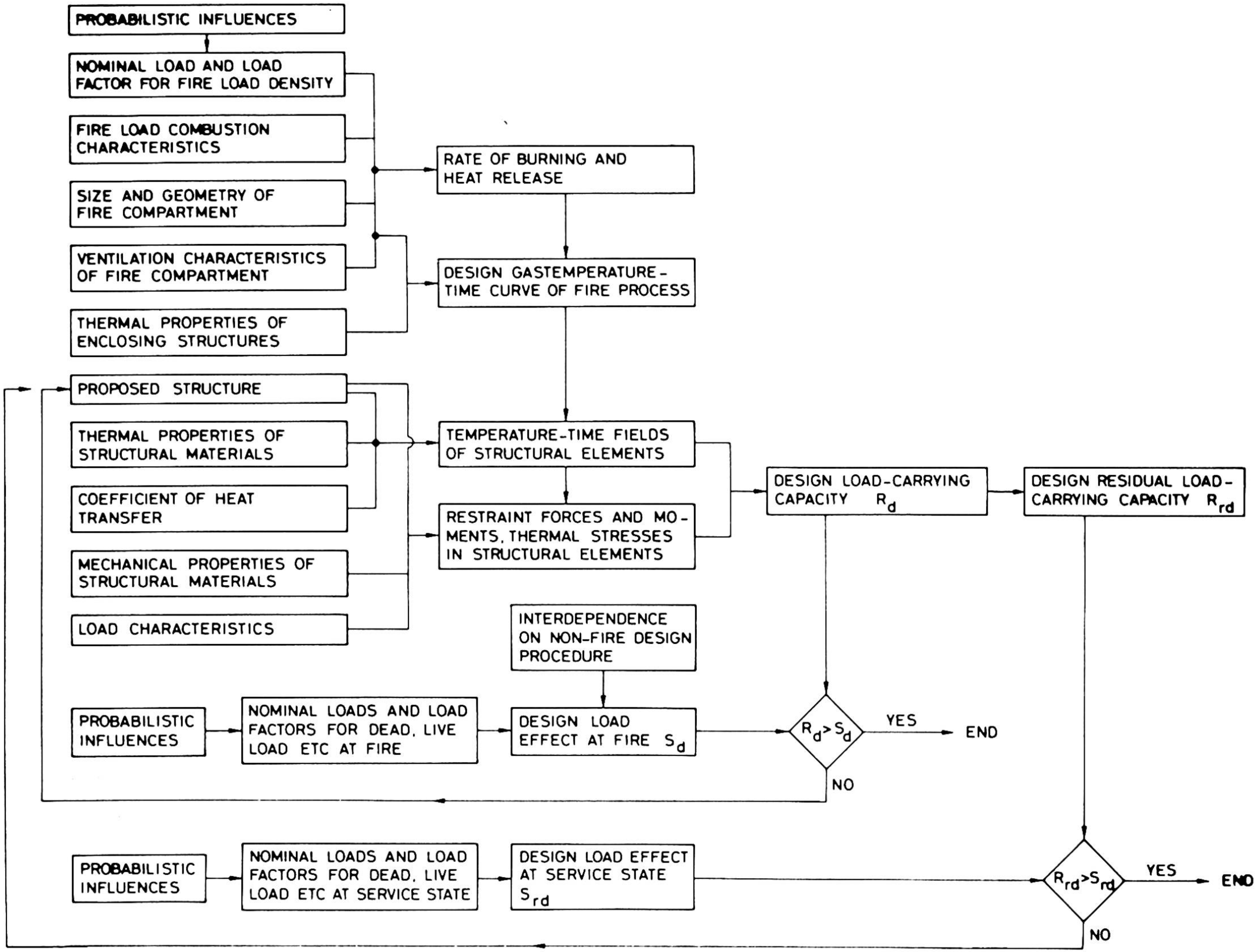


Fig. 1. Procedure of a differentiated fire engineering design of load-bearing structures with additional requirement on re-serviceability after fire

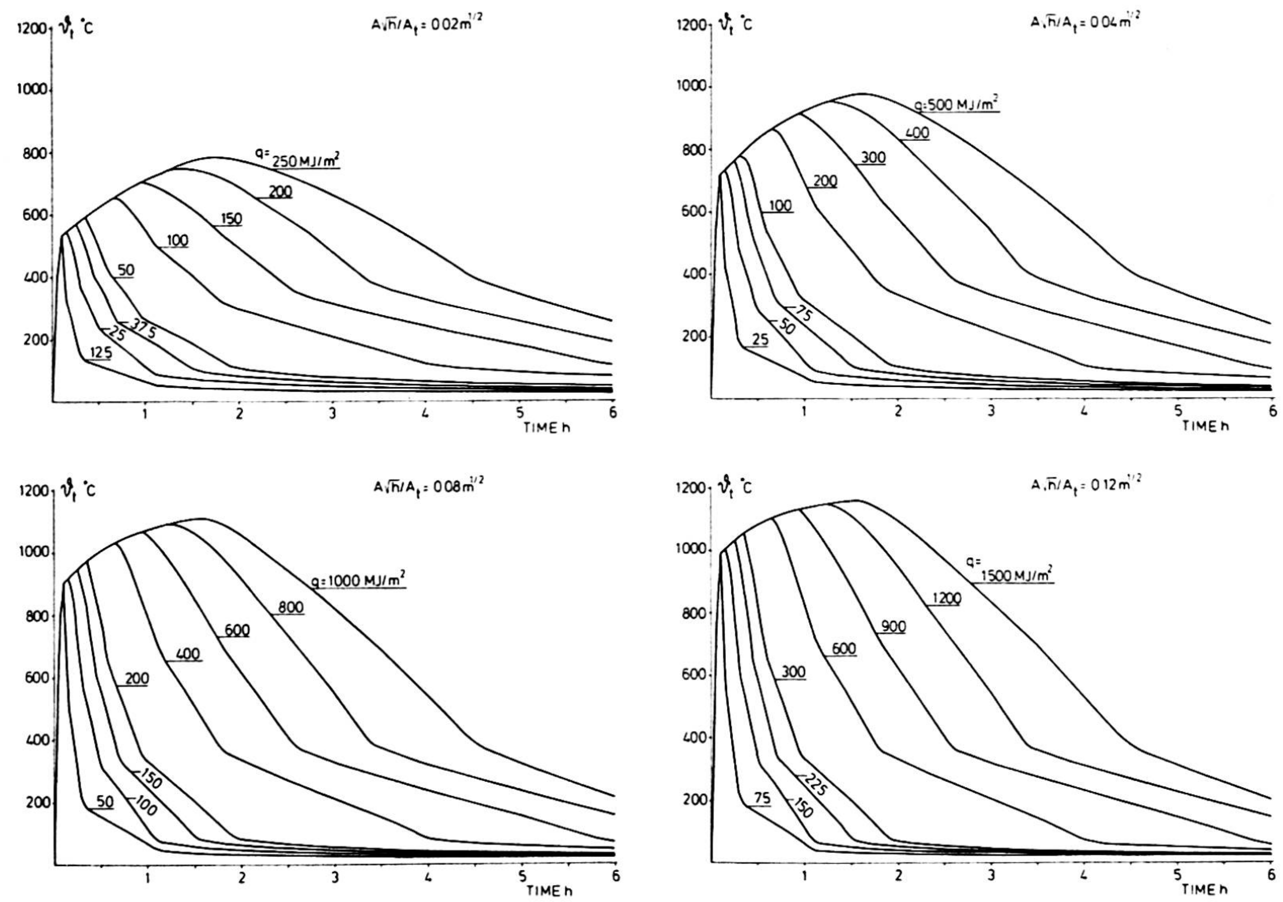


Fig. 2. Gastemperature-time curves ϑ_t-t of the complete process of fire development for different values of the fire load density q and the opening factor $A\sqrt{h}/A_t$. Fire compartment, type A

porosity properties of real fire loads of furniture, textiles, and other interior decorations, which are essential quantities for a combustion description of a fuel bed controlled fire but of minor importance for the development of ventilation controlled fires. Another principle reason is related to the fact that the gastemperature-time curves themselves do not constitute the primary interest of the problem in this connection but an intermediate part of a determination of the decisive quantity, viz. the minimum load-bearing capacity of the structure during a complete fire process. For fuel bed controlled fires, the assumption of ventilation control leads to a structural fire engineering design which will be on the safe side in practically every case, giving an overestimation of the maximum gastemperature and a simultaneous, partly balancing, underestimation of the fire duration. For the minimum load-bearing capacity, the gastemperature-time curves specified in the code are giving reasonably correct results, which has been verified in [3, 4, 10].

The fire exposure curves, specified in the code, apply to a compartment with surrounding structures of a material with a thermal conductivity $\lambda = 0.81\ W \cdot m^{-1} \cdot {}^oC^{-1}$ and a heat capacity $\rho c_p = 1.67\ MJ \cdot m^{-3} \cdot {}^oC^{-1}$ - fire compartment, type A. Entrance parameters for the curves are the fire load density q ($MJ \cdot m^{-2}$), and the ventilation characteristics of the fire compartment, expressed by the opening factor $A\sqrt{h}/A_t$ ($m^{1/2}$). A = the total area of the window and door openings (m^2), h = the mean value of the heights of window and door openings, weighed with respect to each individual opening area (m), and A_t = the total interior area of the surface bounding the compartment, opening areas included (m^2). The fire load density q is defined according to the formula

$$q = \frac{1}{A_t} \Sigma\, m_\nu H_\nu \qquad (MJ\cdot m^{-2})$$

where m_ν = the total weight (kg), and H_ν = the effective heat value ($MJ\cdot kg^{-1}$) for each individual combustible material ν of the fire compartment.

In the design procedure, a transfer can be done between fire compartments of different thermal properties of the surrounding structures according to simple rules, based on fictitious values of the opening factor and the fire load density [3, 4, 5, 7]. By introducing such a transfer system, design diagrams and tables – facilitating a practical application – can be limited to one type of fire compartment, viz. type A.

A differentiated design according to the described procedure can be carried through in practice today in a comparatively general extent for fire exposed steel structures. The practical application then is facilitated by the availability of a manual [4], comprising a comprehensive design basis in the form of tables and diagrams which directly are giving the maximum steel temperature for a differentiated, complete fire process and the corresponding load-bearing capacity. The manual has been approved for a general practical use in Sweden by the National Board of Physical Planning and Building.

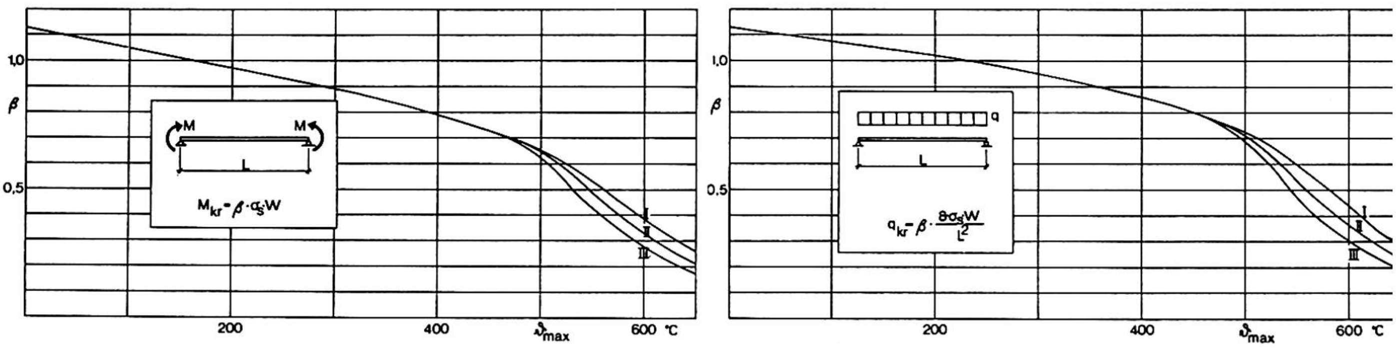


Fig. 3. Load-bearing capacity (M_{kr}, q_{kr}) for two types of loading at a simply supported steel beam of constant I cross section. Curves I, II, and III correspond to a rate of heating of 100, 20, and 4 $^{o}C\cdot min^{-1}$, respectively, and a rate of subsequent cooling = 1/3 of rate of heating.
ϑ_{max} = maximum steel temperature, σ_s = yield point stress at ordinary room temperature, and W = elastic modulus of cross section

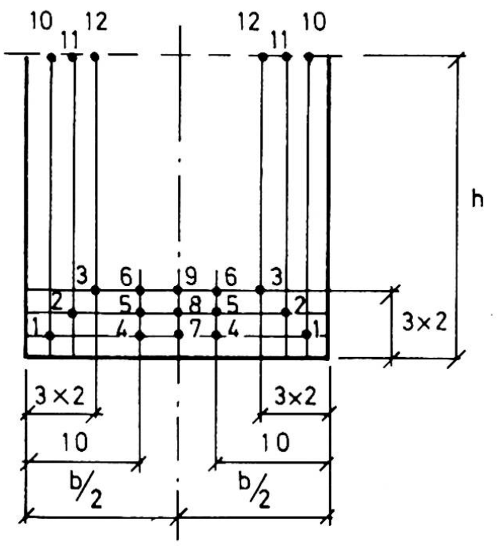
In comparison with steel structures, fire exposed reinforced and prestressed concrete structures generally are characterized by an essentially more complicated thermal and mechanical behaviour. In consequence, the basis of a differentiated structural fire engineering analysis and design is considerably more incomplete for concrete structures – cf., for instance, [5, 6, 7, 11], in which summary reports are given on the present state of knowledge. Completing the manual on fire exposed steel structures [4], another manual is in course of preparation – to be edited by the National Board of Physical Planning and Building – with the purpose to facilitate the practical application of the differentiated design procedure also to other types of load-bearing structures – reinforced and prestressed concrete structures, aluminium structures, and wooden structures. A design guidance for fire exposed partitions of various materials is included, too.

Fragmentary examples of the design basis quoted are given in Fig. 3 [4], Table 1 [4], and Table 2 [7].

Table 1. Maximum steel temperature ϑ_{max} for a fire exposed, insulated steel structure at varying fictitious fire load density q_f ($MJ \cdot m^{-2}$), and structural parameter $A_i \lambda_i / V_s d_i$) ($W \cdot m^{-3} \cdot {}^oC^{-1}$). Fictitious opening factor $(A\sqrt{h}/A_t)_f = 0.04\ m^{1/2}$. A_i = interior jacket surface area of insulation per unit length (m), d_i = thickness of insulation (m), λ_i = thermal conductivity of insulating material ($W \cdot m^{-1} \cdot {}^oC^{-1}$), and V_s = volume of steel structure per unit length (m^2)

q_f	$A_i \lambda_i / (V_s d_i)$												
	50	100	200	400	600	1000	1500	2000	3000	4000	6000	8000	10000
25	25	35	50	70	85	115	140	170	210	245	290	330	365
50	35	50	75	115	150	200	245	290	350	395	450	505	540
75	45	65	100	155	200	260	325	380	450	500	565	615	650
100	50	80	125	190	245	320	395	450	525	575	640	685	715
200	85	135	210	310	385	490	575	635	710	755	800	825	835
300	115	180	275	410	500	615	700	755	815	845	875	890	895
400	140	225	345	505	605	720	800	845	890				
500	170	270	415	585	685	790	860	895					

Table 2. Maximum temperature ϑ_{max} during a complete process of fire development in different points of a rectangular concrete beam, fire exposed from below on three surfaces, at varying values of the fictitious fire load density q_f($MJ \cdot m^{-2}$), and the cross-sectional width b (m). Fictitious opening factor $(A\sqrt{h}/A_t)_f = 0.04\ m^{1/2}$. The temperature values are computed for a cross-sectional height h = 0.2 m but are applicable with sufficient accuracy also to other values of h > 0.2 m



q_f	b/2	1	2	3	4	5	6	7	8	9	10	11	12
	0.04	345	260					300	260	240	225	215	
	0.06	335	185	170				230	185	170	210	140	140
	0.08	335	180	135				210	145	135	205	115	105
50	0.10	335	180	125	210	125	105	210	125	105	205	110	95
	0.125	335	180	120	210	125	100	205	110	95	205	110	85
	0.15	335	180	120	205	120	95	205	105	90	205	105	85
	0.20	335	180	120	205	115	95	205	105	85	205	105	85
	0.30	335	180	120	205	110	95	205	105	85	205	105	85
	0.04	500	425					465	425	400	380	370	
	0.06	480	325	295				370	315	295	315	245	245
	0.08	480	300	235				325	255	230	305	185	180
100	0.10	480	295	210	315	215	190	315	215	190	305	180	140
	0.125	480	295	200	310	200	170	305	180	150	305	175	125
	0.15	480	295	200	310	190	155	305	175	135	305	175	125
	0.20	480	295	200	310	185	150	305	175	120	305	175	120
	0.30	480	295	200	305	180	150	305	175	120	305	175	120
	0.04	690	610					655	610	585	570	555	
	0.06	650	495	460				545	485	460	460	400	395
	0.08	645	450	375				480	400	370	440	310	300
200	0.10	645	435	335	455	345	315	455	345	315	435	280	235
	0.125	645	435	315	450	325	270	435	295	245	435	275	200
	0.15	645	435	315	445	305	245	435	280	210	435	270	195
	0.20	645	430	315	440	300	240	435	270	190	435	270	190
	0.30	645	430	315	440	295	235	435	265	190	435	270	190
	0.04	795	740					775	740	720	705	690	
	0.06	755	625	585				670	610	585	580	520	520
	0.08	740	570	490				600	515	485	535	415	400
300	0.10	740	550	440	565	455	415	565	455	415	525	370	320
	0.125	740	545	415	550	425	370	535	390	335	525	355	275
	0.15	740	540	410	535	400	330	525	365	290	520	350	265
	0.20	740	540	410	535	390	320	520	350	260	520	350	260
	0.30	740	540	410	530	385	315	520	345	250	520	345	255

The summarily presented, differentiated design procedure is to be seen as an attempt to build up a logical system for a structural fire engineering design, based on functional requirements. The system is well devoted to stimulate the architects and structural engineers to solve the fire engineering problems in a qualified way over a design procedure which is equivalent to the non-fire, structural design, conventionally applied. The design system is not homogeneous, as regards the present basis of knowledge for the different design steps, which could be put forward as a criticism of the system. However, such a remark is not essential. Instead, this fact should be used as an important information on how to systematize a future research for enabling a successive improvement of the design system

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SUMMARY

On the basis of the general functional requirements, a differentiated, analytical procedure is presented for a fire engineering design of load-bearing structures. Examples are given. The method is approved for a general practical use in Sweden by the National Board of Physical Planning and Building.

RESUME

Sur la base des fonctions générales des constructions une méthode analytique différenciée est présentée pour la détermination de la sécurité au feu des éléments de structure. Des exemples sont donnés. La méthode est approuvée par les autorités pour l'utilisation pratique en Suède.

ZUSAMMENFASSUNG

Es wird ein differenziertes Verfahren für die brandtechnische Dimensionierung von Baukonstruktionen beschrieben, das sich auf direkte Funktionsforderungen stützt. Das Verfahren ist von den Behörden für eine generelle, praktische Anwendung in Schweden zugelassen.