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Lund Institute of Technology, Sweden, 1970

THE POSSIBILITIES OF PREDICTING THE FIRE BEHAVIOUR OF STRUCTURES ON THE BASIS OF DATA FROM STANDARD FIRE RESISTANCE TESTS

A critical analysis with respect to varying characteristics of the fire load and the fire compartment

By Prof. Dr. Ove Pettersson, Lund Institute of Technology, Sweden

1. Introductory remarks on the standard fire resistance test

The different national prescripts and the corresponding ISO Recommendation - R 834, September 1968 - concerning fire resistance tests of elements of building construction have been developed on the basis of the classification requirements, stipulated in the building codes and regulations.

The scope of the test method consists of a determination of the fire resistance of an element of building construction, defined as that period of time which extends from the beginning of a fixed heating process to an instant when the element no longer complies with the functional requirements to be fulfilled. The function required then can be a) a load-bearing function (e.g. a column or a beam), b) a separating function (e.g. a partition or a non-load-bearing wall), and c) a load-bearing and separating function (e.g. a load-bearing wall or a floor).

Fundamental for a fire resistance test is that the test results shall be reproducable. This necessitates very accurate detail specifications of the test conditions, as regards the preparation of the test specimens and the characteristics of heating, loading and restraint during the test.

Fundamental for a fire resistance test further is that the test results can be used in a structural fire engineering design as informations, representative for real conditions. This presupposes that the test characteristics and results have to be specified, measured and reported in such an extent and with such a degree of accuracy that the element of building construction, corresponding to the test specimen, can be analysed for a fire action with regard to its real functional behaviour in the complete structure. In detail accurately specified, measured and reported data for a fire resistance test also will facilitate a qualified classification and an international utilization of the test data in countries with different classification requirements.

In certain essential respects the present ISO Recommendation on fire resistance tests of elements of building construction has not been given such a form that the fundamental aims of the test, summarized above, can be guaranteed. Especially, this is the fact to the heating and restraint conditions, specified in the recommendation.

As concerns the heating conditions, the recommendation only specifies a time curve of the furnace temperature (the standard time-temperature curve), connected to additional directions for temperature tolerances and measurements. Such a specification is not sufficient as an external characteristic for a determination of the time-temperature fields in an element of building construction exposed to a fire. In addition, another decisive factor in this connection is the coefficient of heat transmission for the exterior surfaces of the fire exposed element, which coefficient primarily is influenced by the convection and radiation conditions. For a prescribed furnace time-temperature curve the convection and radiation characteristics can vary considerably from one furnace to another, depending on the detail design of the furnace and the type of fuel. Of that reason comparative estimations of test results, obtained in different fire engineering laboratories, can be very difficult - and sometimes impossible - to carry through. In order to facilitate such comparisons of test results, it is highly urgent that the existing ISO Recommendation will be completed on this point, for instance by including a specification that the thermal properties of the furnace shall be calibrated with reference to a well-defined standard test specimen and be given in terms of that variation in the coefficient of heat transmission with the time which is associated with the standard time-temperature curve. This calibration curve of the furnace generally ought to be included in the test reports.

As concerns the restraint conditions of a test specimen, it is well-known that variations of restraint characteristics considerably can influence the structural behaviour and the time of fire resistance for an element of building construction. Usually the effect of increased degree of restraint is beneficial for the fire resistance of a structural element but sometimes a detrimental effect can be introduced. For instance, a thrust restraint can accelerate an instability failure in fire. For a concrete structural element, a thrust restraint also can give rise to an increased risk of spalling. For a statically indeterminate slab of reinforced concrete under fire action on one side, a moment restraint can cause a serious crack formation in weakly reinforced regions and owing to that initiate a shear fracture of the structure.

From these facts it is obvious that results from fire resistance tests, carried out under undefined restraint conditions - which is not infrequent today - are very difficult to use in a differentiated structural fire engineering design as well as for a qualified classification. Additions to the present ISO Recommendation on this point - successively leading to, for instance, a series of precisely defined restraint conditions, relevant to real structures - consequently have high degree of priority.

Problems of the type touched upon above have been discussed thoroughly within the Working Groups 5 and 8 of ISO/TC 92 during the last years. Informations on these discussions are given in the documents of the working groups. As a first step on the way to a fire resistance test of elements of building construction, which is functionally, essentially better adapted with regard to the fundamental aims of the test, a draft proposal for a revision of the existing ISO Recommendation will be presented at the next plenary meeting of ISO/TC 92 in the autumn 1971. To this draft proposal commentaries will be attached with the intention to serve as a summary guidance for a planning, performance and reporting of a fire resistance test in conformity with the fundamental principles outlined in the above.

With these introductory remarks as a background, the following treatment will be devoted to a critical discussion with respect to varying characteristics of the fire load and the fire compartment of how data from standard fire resistance tests can be used for predicting the behaviour of structures or structural elements in real fires. First a summary survey will be given of some essential characteristics of the process of fire development and then the main problem will be briefly analysed on the basis of two different types of methods for a differentiated structural fire engineering design.

2. Some basic characteristics of the process of fire development

In each individual case a qualified structural fire engineering design must be based on as real characteristics as possible for the complete process of fire development, composed of the phases of ignition, flaming or heating and cooling (Fig. 1). These characteristics depend on several influences with as the most important:

(a) the amount and type of combustible materials in the compartment (the fire load),

(b) the porosity and particle shape of the fire load,

(c) the distribution of the fire load in the compartment,

(d) the amount of air per unit time supplied to the compartment,

(e) the geometry of the compartment, and

(f) the thermal characteristics of the structures, enclosing the compartment.

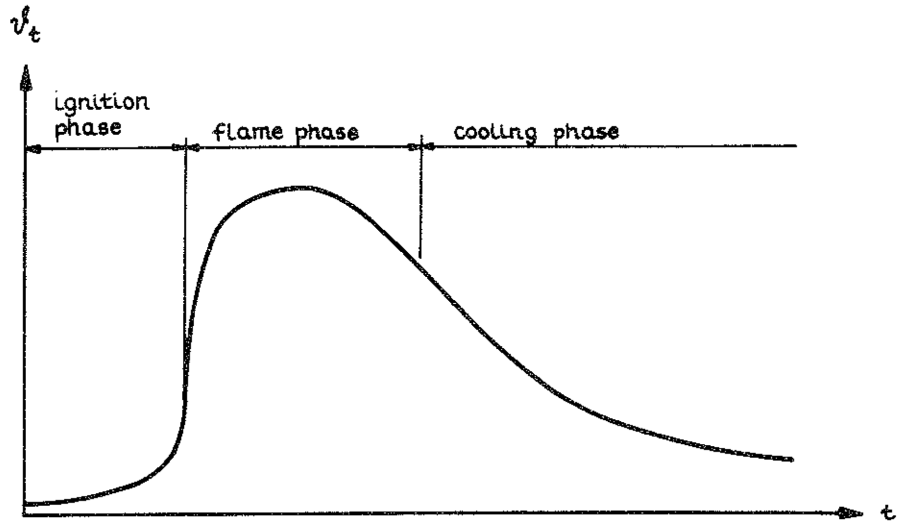


Fig. 1. Gastemperature-time curve (ϑ_t - t) of the complete process of fire development, comprising the phases of ignition, flaming or heating and cooling

In spite of a large number of very important investigations reported in the literature, our present state of knowledge on the detail characteristics of compartment fires - in the main limited to the flame phase - is far from satisfactory.

Somewhat simplified, fully-developed compartment fires can be divided into two types of behaviour [1]. For the first type, the combustion during the flame phase is controlled by the ventilation of the compartment with the burning rate approximately proportional to the air supply through the openings of the compartment and not in any decisive way dependent on the amount, porosity and particle shape of the fuel. For the second type, the combustion during the flame phase is controlled by the properties of the fuel bed with the burning rate determined by the amount, porosity and particle shape of the fuel and largely independent of the air supply through the openings. The boundary between the two kinds of fire behaviour is not sharply marked.

The phenomenon is illustrated a little more in detail by Fig. 2 [2], which shows the experimentally determined relation between the average burning rate R and the air flow factor $A\sqrt{h}$ or the opening factor $A\sqrt{h}/A_t$ at varying fire load $\bar{q}$ for fully-developed fires with piles of 4.5 cm wooden sticks. A = the total area of the window openings of the compartment, h = the height of the window openings, A_t = the total area of the surfaces bounding the compartment, and $\bar{q}$ = the fire load per unit area of the floor. The figure demonstrates clearly the two regions of ventilation controlled and fuel bed controlled fires with the burning rate R linearly dependent, respectively largely independent of the air flow factor.

As concerns ventilation controlled fires in compartments, we know from very extensive experimental investigations in varying scales - summarized in [3] - that the average burning rate for the active part of a fire $R = R_{80-30}$ (cf. Fig. 3) approximately is related to the air flow factor $A\sqrt{h}$ by the relation

$$R = kA\sqrt{h} \qquad (1)$$

where k is a constant. For fire loads of piles or cribs of wood, fiber insulation board cribs and furniture, it is stated in [3] on the basis of experiments, carried out in Denmark, Japan, USA, UK and USSR, that the value of k is about 5.5 to 6 $kg \cdot min^{-1} \cdot m^{-5/2}$, provided the area A is approximately one-quarter of the area of one side of the compartment, or less, and provided there is sufficient fuel for the burning rate of the fire to be ventilation controlled. At very small area A the coefficient k can increase to values of the level 9 to 10 $kg \cdot min^{-1} \cdot m^{-5/2}$.

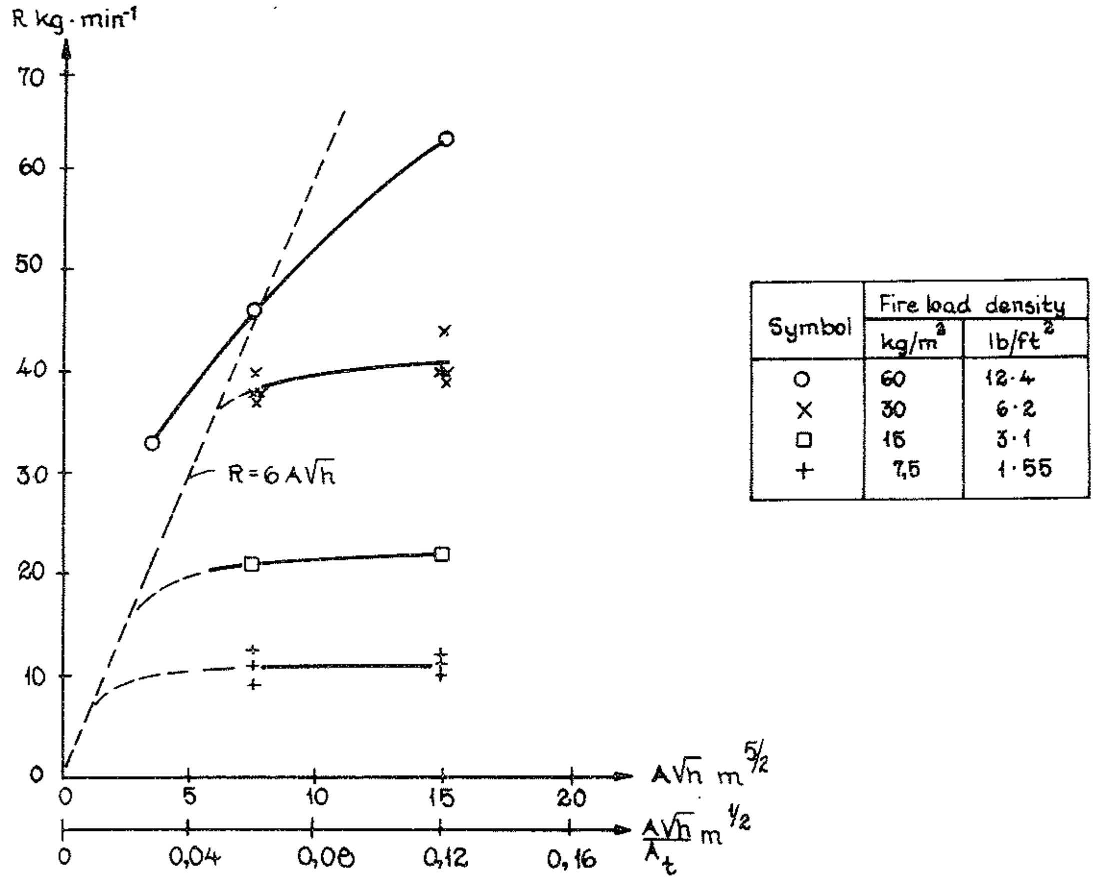


Fig. 2. Relation between average burning rate R (kg/min) and air flow factor $A\sqrt{h}$ ($m^{5/2}$) or opening factor $A\sqrt{h}/A_t$ ($m^{1/2}$) at varying fire load $\bar{q}$ (kg/m^2 floor area), determined for fully-developed fires with piles of 4.5 cm wooden sticks in a compartment 7.7 x 3.7 x 3.0 m [2]

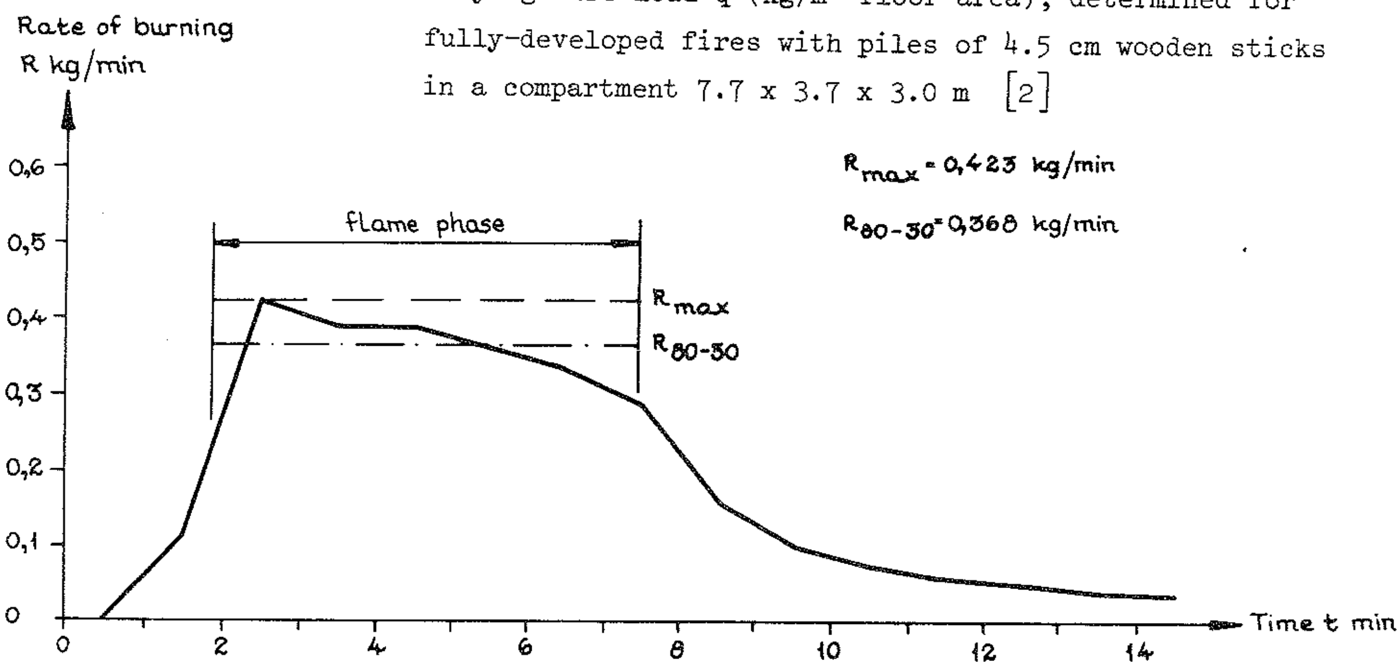
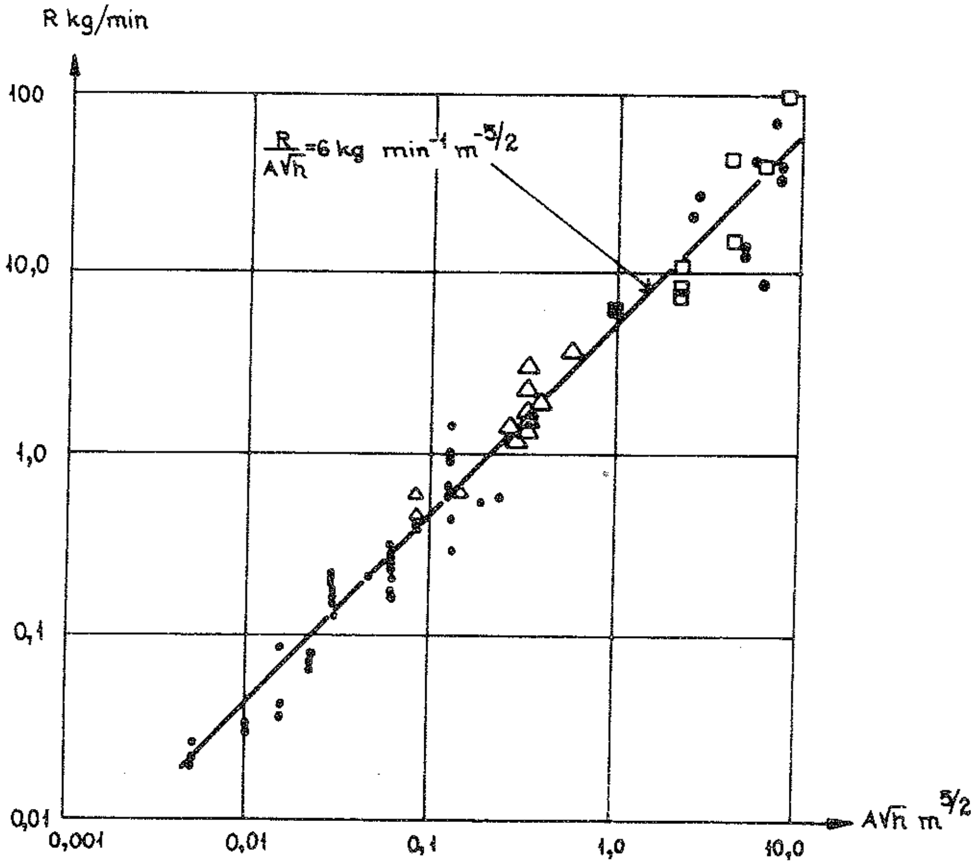


Fig. 3. Burning rate-time curve (R - t) of the complete process of fire development, determined for a model scale fire with pile of 2.5 cm wooden sticks. R_{max} = the maximum burning rate, R_{80-30} = the average burning rate, corresponding to a weight loss of the fuel from 80 to 30 percent of the initial weight [5]

From more detailed summaries of the results from ventilation controlled fires in compartments, it is evident that the results are characterized by a not inconsiderable deviation from the values given by Eq. (1) - cf. Fig. 4 [4]. The deviation indicates that the burning rate R depends not only on the air flow factor $A\sqrt{h}$ but also, in some extent, on others of the influences listed above.



Experiment	Floor area ft^2	m^2	Symbol
J.F.R.O.	1	0,087	●
	4	0,37	•
	9	0,83	△
J.F.R.O.	34	3,2	▩
J.F.R.O.	100	9,0	●
Kawagoe	11	1,0	△
	≈ 100	≈9,0	□

Fig. 4. Relation between average burning rate R and air flow factor $A\sqrt{h}$, determined from a very large number of fully-developed fires in compartments of varying scale [4]

The combined effect on the burning rate R of variations in the air flow factor $A\sqrt{h}$ and the porosity factor of the fire load ϕ has recently been studied in an experimental investigation, carried out by Leif Nilsson [5]. The investigation contains 175 experiments on ventilation controlled as well as fuel bed controlled fires in cubic compartments of three different scales with the fire load composed of cribs of wooden sticks. For all experiments the following influences have been kept constant: the magnitude of the fire load q (2 kg per unit area of the total surface bounding the compartment), the thickness of the wooden sticks b (2.5 cm), and the thermal characteristics of the structures enclosing the compartment (asbestos sheets, 1 cm thick and with the density 1020 kg per m^3). Under these conditions the results of the investigation can be summarized by the following approximate formula, as concerns the average burning rate R_{80-30} (kg per min):

$$R_{80-30} = \frac{1}{\bar{k}} \left[(6.3\phi + 3.5)\, A\sqrt{h} - 0.17\phi + 0.15 \right] \qquad (2)$$

where $\bar{k}$ is a coefficient, which depends on the opening factor of the compartment $A\sqrt{h}/A_t$ ($m^{1/2}$) according to Fig. 5. The air flow factor $A\sqrt{h}$ is then to be in $m^{5/2}$. The porosity factor of the fire load ϕ ($cm^{1.1}$) is defined according to Gross by the relation [6]

$$\phi = N^{0.5} \cdot b^{1.1} \cdot \frac{A_v}{A_s} \qquad (3)$$

where

$$A_s = 2\, nb \,\{2\, NL + b \left[N - n(N-1) \right] \} \qquad (4)$$

$$A_v = (L - nb)^2 \qquad (5)$$

In these equations, n is the number of sticks per layer, N is the number of layers in the wood pile, L (cm) is the length and b (cm) the width of each individual wood stick, A_s (cm^2) is the initial surface area of all sticks in the pile exposed to the air, and A_v (cm^2) is the initial open vent surface area of vertical shafts through the pile.

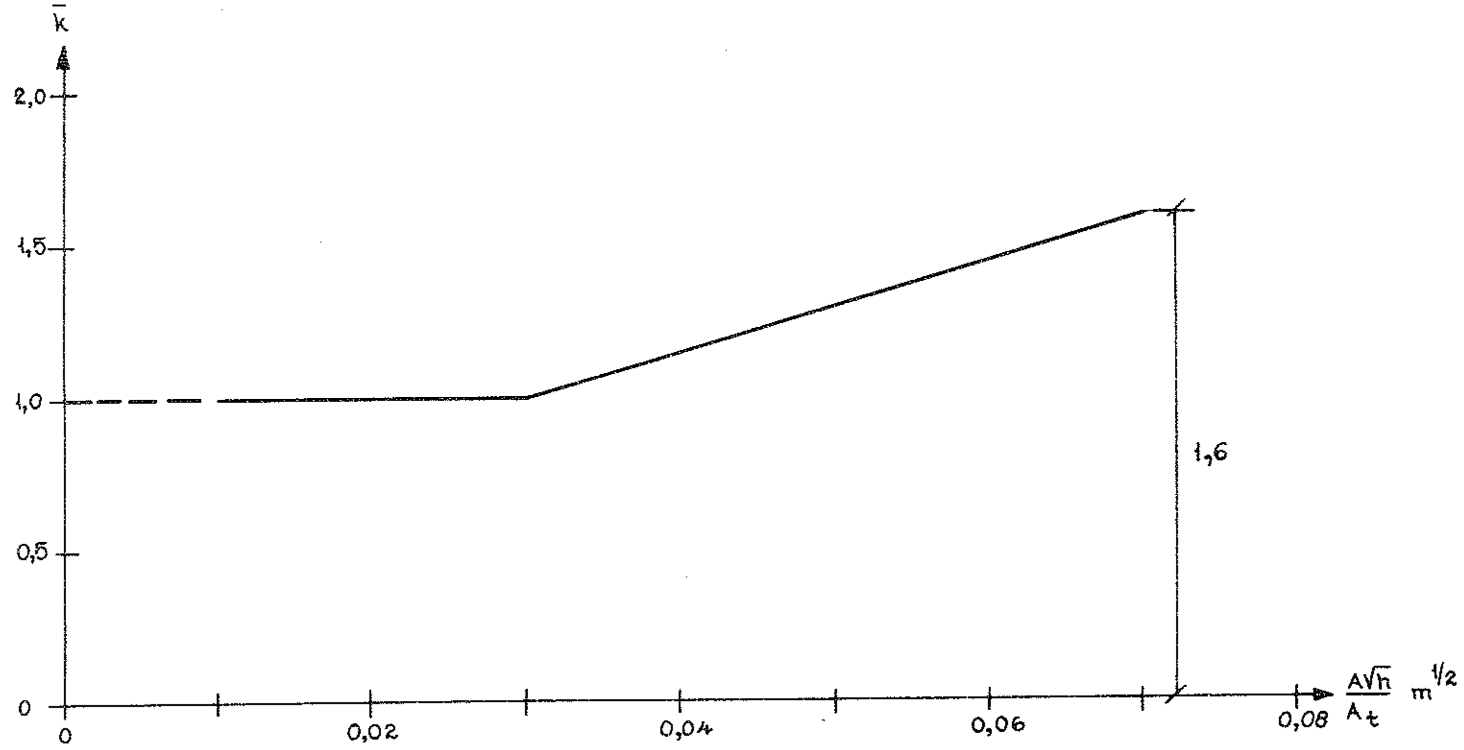


Fig. 5. Variation with the opening factor $A\sqrt{h}/A_t$ of the coefficient $\bar{k}$, entering into Eq. (2) [5]

The applicability of Eq. (2) is connected to the following secondary conditions:

(a) If $A\sqrt{h} < 0.027\ m^{5/2}$, calculate R_{80-30} from the relation

$$R_{80-30} = 9.25\ A\sqrt{h} \quad (kg/min) \qquad (6)$$

(b) If $\phi < 0.1\ cm^{1.1}$, calculate R_{80-30} by linear interpolation between the two points ($\phi = 0$, $R = 0$) and [$\phi = 0.1$, R according to Eq. (2)]

(c) If $\phi > 0.5\ cm^{1.1}$, put $\phi = 0.5$

(d) If $A\sqrt{h}/A_t > 0.07\ m^{1/2}$, insert into Eq. (2) that value of $A\sqrt{h}$ which corresponds to $A\sqrt{h}/A_t = 0.07$.

In combination with these secondary conditions Eq. (2) gives the average burning rate of the active part of a fire for the region of ventilation controlled as well as for the region of fuel bed controlled fires. The boundary between the two regions is approximately determined by the opening factor $A\sqrt{h}/A_t = 0.07\ m^{1/2}$.

As concerns <u>fuel bed controlled fires</u>, the validity of Eq. (2) is limited to a fire load $q = 2\ kg/m^2$ of the total surface bounding the compartment and consisting of a pile of wooden sticks with the thickness $b = 2.5$ cm.

If we assume that the boundary between the two types of fire behaviour simultaneously is determined by a ventilation controlled fire, with the average burning rate approximately given by Eq. (1), and by a fuel bed controlled fire, with the average burning rate characterized by a largely constant rate of increase in the depth of the charred layer of the wooden sticks, then the following relation can be deduced for the transition point between the two regions of fire:

$$\left(\frac{A\sqrt{h}}{A_t} \right)_{trans} = c\,\frac{q}{b} \qquad (7)$$

Hence, it follows that the upper limit of the opening factor with respect to ventilation controlled fires is directly proportional to the fire load q, referred to a unit area of the surface bounding the compartment, and inversely proportional to the thickness b of the sticks, constituting the fire load.

At known value of the factor c, which is not invariable, Eq. (7) approximately gives the opening factor corresponding to the transition point and then the appurtenant rate of burning can be calculated according to Eq. (1) for the fuel bed controlled fires, actual for larger values of the opening factor than $(A\sqrt{h}/A_t)_{trans}$. Unfortunately, the coefficient c is unknown at the present, even for fire loads with very simple geometrical characteristics.

From the discussion now carried through, the following conclusions can be drawn. For ventilation controlled fires, the average burning rate of the active part of the fire can be determined from Eq. (1) for different types of fire loads, furniture included, with an accuracy which is sufficient in most practical cases of a structural fire engineering design. For fuel bed controlled fires with an essentially more complicated behaviour, the present state of knowledge is too incomplete for enabling a satisfactory corresponding calculation of the burning rate in practice with the fire load consisting of furniture, very difficult to define with regard to the properties of porosity. In such a position it seems reasonable to base a differentiated structural fire engineering design on characteristics for the process of fire development which constantly have been determined on the assumption of the fire to be ventilation controlled. For fuel bed controlled fires, such a simplifying assumption leads to a fire engineering design which will be on the safe side in practically every case.

A philosophy of this kind is characteristic for a comprehensive theoretical study of wood fuel fires in compartments, recently published by Magnusson and Thelandersson [7]. In this work a systematized method is deduced for a calculation over the heat balance and mass balance equations of the gastemperature-time curve of the complete process of fire development. The design procedure, which can be seen as a generalization of the more limited methods previously presented by Kawagoe-Sekine [8] and Ödeen [9], contains a computer programme which enables a consideration of temperature dependant thermal properties and critical temperatures for decomposition of the materials entering into the surrounding structures, initial moisture content in the surrounding structures, effect of heat stored in structures enclosed in the compartment, and changes in size and shape of window and door openings during the process of fire development. The procedure is applicable to compartments, which contain up to three different types of sorrounding structures with one of these structures composed of up to three different materials.

A practical application of the design procedure presupposes that the time variation of the combustion rate, specified as the quantity of released heat per unit of time, is known. Such a variation can easily be given for well-defined fuels without any smoulder phase. For not well-defined fuels - for instance wood fuels - a determination of the time-variation of the amount of the released heat per unit of time is connected to great experimental difficulties. At present essential informations are lacking concerning such problems as a transformation of the burning rate expressed as weight loss per unit of time to a burning rate given as the quantity of released heat per unit of time or a division of the total amount of the released heat to the flame and cooling periods.

In this state of knowledge the problem has been tackled in [7] in the following way. For such full-scale experiments with wood fuel fires in compartments which have been reported in the literature in a sufficiently accurate manner, the authors have carried through a theoretical determination for each individual experiment of that time curve for the released quantity of heat per unit of time, which gives the best agreement for the complete process of fire development between the theoretically calculated and experimentally determined gastemperature-time curves for the compartment. The results from such calculations have enabled a construction of representative, simplified time curves for the quantity of released heat per unit of time under varying presumptions. On the basis of these time curves then the authors have carried out in a systematic way very extensive calculations of the gastemperature-time curve of the complete process of fire development for varying assumptions concerning the geometrical and thermal characteristics of the room, the opening factor $A\sqrt{h}/A_t$ and the fire load q, defined as the corresponding heat value per unit area of the total surface bounding the fire room. As a fragmentary illustration of the results presented, Fig. 6 reproduces theoretically determined gastemperature-time curves ($\vartheta_t - t$) at varying fire load q and opening factor $A\sqrt{h}/A_t$ for a compartment with surrounding structures, 20 cm in thickness and made of a material with a thermal conductivity $\lambda = 0.7$ kcal per m per h per ^{o}C and a heat capacity $\gamma c_p = 400$ kcal per m^3 per ^{o}C as representative average values within the temperature range associated with fires.

In combination with rules for a transformation of gastemperature-time characteristics for a compartment with given thermal properties of the surrounding structures to the gastemperature-time curves according to Fig. 6 - for instance, via fictitious values of the fire load q and the opening factor $A\sqrt{h}/A_t$ - these latter curves can be used as a basis for a differentiated structural fire engineering design. As an illustration of the effect of varying thermal properties of the surrounding structures, Fig. 7 shows theoretically determined gastemperature-time curves for eight different types of compartments with an opening factor $A\sqrt{h}/A_t = 0.04$ $m^{1/2}$ and with a fire load $q = 60$ Mcal/m^2 [7].

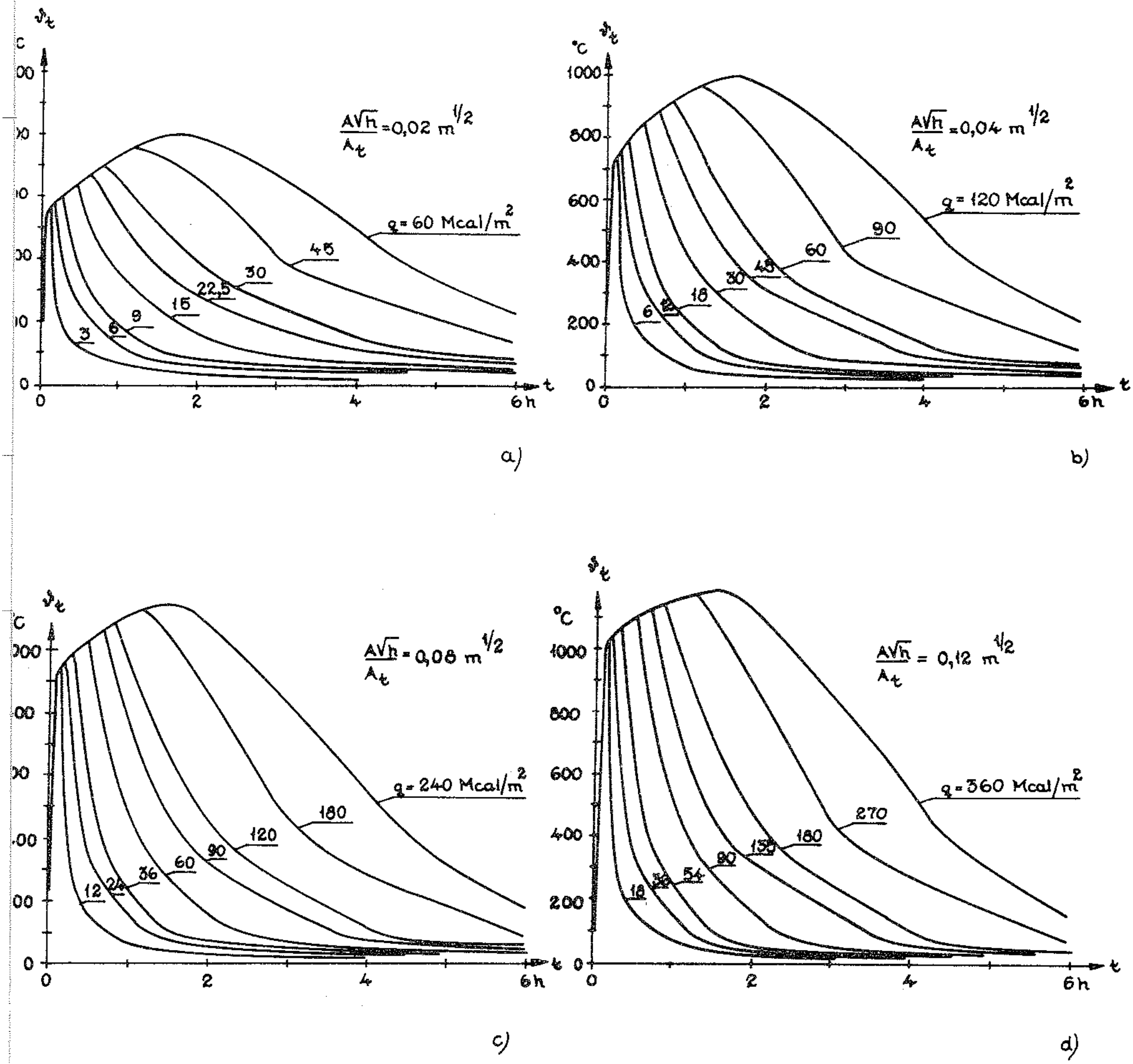


Fig. 6. Gastemperature-time curves (ϑ_t - t) of the complete process of fire development for different values of the opening factor $A\sqrt{h}/A_t$ ($m^{1/2}$) and the fire load q ($Mcal/m^2$ of the total surface bounding the compartment). The curves correspond to a wood fire burning in a room enclosed by structures, 20 cm in thickness and made of a material with a thermal conductivity $\lambda = 0.7$ kcal/m·h·°C and a heat capacity $\gamma c_p = 400$ kcal/m³°C as representative average values within the temperature range actual [7]

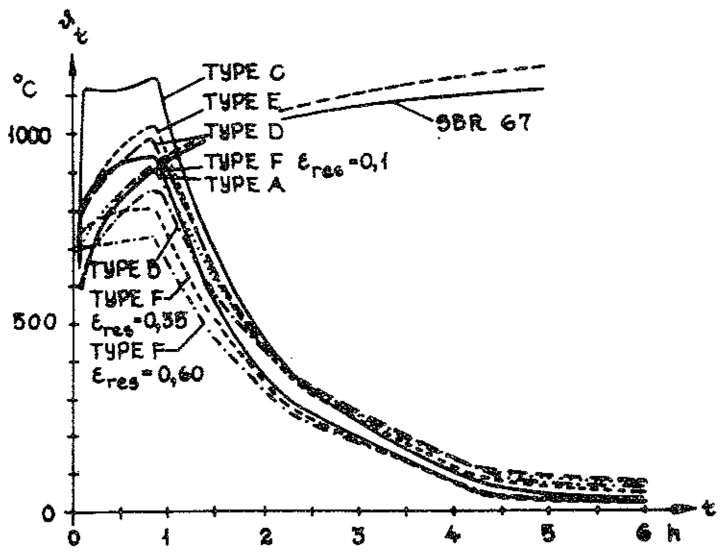


Fig. 7. Gastemperature-time curves (ϑ_t - t) for different types of compartments at an opening factor $A\sqrt{h}/A_t = 0.04\ m^{1/2}$ and a fire load q = 60 Mcal/m^2. Type A corresponds to the compartment, valid for the curves in Fig. 6. Type C is characterized by bounding structures of lightweight concrete with a density $\gamma = 500\ kg/m^3$, type F by bounding structures mainly of sheet steel, 2 mm in thickness [7]

3. Methods for a differentiated structural fire engineering design

The present development of the building codes and regulations in the direction towards functionally better founded requirements continuously has increased the necessity of methods for a differentiated structural fire engineering design. During the last years several such design methods have been presented in the literature. Mainly, these methods can be divided into two different groups with respect to the basic data of the process of fire development. The methods belonging to the first group, then are characterized by a design procedure, directly based on gastemperature-time curves of the complete process of fire development, specified in detail according to Fig. 6. Characteristic for the methods of the second group is a design procedure with the varying properties of the fire development taken into consideration over a fictitious time of fire duration, connected to the standard time-temperature curve. In all methods of the two groups, the effect of the cooling phase of the fire is included.

3.1 Structural fire engineering design, directly based on differentiated gastemperature-time curves

Related to a load-bearing structure or structural element, a differentiated fire engineering design according to the methods of the first-mentioned group comprises the following main components [10], [11]:

(a) The choice, in each particular case, of representative combustion characteristics of the fire load.

(b) The determination for these combustion characteristics of the gastemperature-time curve and the convection and radiation properties of the complete process of fire development, taking into account the geometry of compartment, the size and shape of window and door openings and the thermal characteristics of the structures, enclosing the compartment.

(c) The determination of the corresponding temperature-time fields in the structure or the structural element, exposed to fire.

(d) The determination - on the basis of data according to (c) and data on the strength and deformation properties of the structural materials in temperature range, associated with fires - of the point of time for collapse at prescribed loading or, alternatively, of the minimum loadbearing capacity of the structure or the structural element for the process of fire development valid.

In a differentiated fire engineering design of a separating structure or structural element the design component (d), in most cases, is out of interest.

For making such a differentiated fire engineering design practically applicable for the structural engineer, it is necessary to complete the procedure with design diagrams for different types of structures or structural elements. Examples of such diagrams are given in Figs. 8 to 14 with the diagrams, facilitating a temperature determination, based on gastemperature-time curves of the compartment according to Fig. 6.

In Fig. 8a-d [12], [13] design curves are presented, giving directly the maximum steel temperature $\vartheta_{s_{max}}$ for a non-insulated steel structure, exposed to fire on all surfaces, at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient F_s/V_s. The resultant emissivity $\varepsilon_r = 0.7$. F_s is the fire exposed surface and V_s the volume of the steel structure per unit of length.

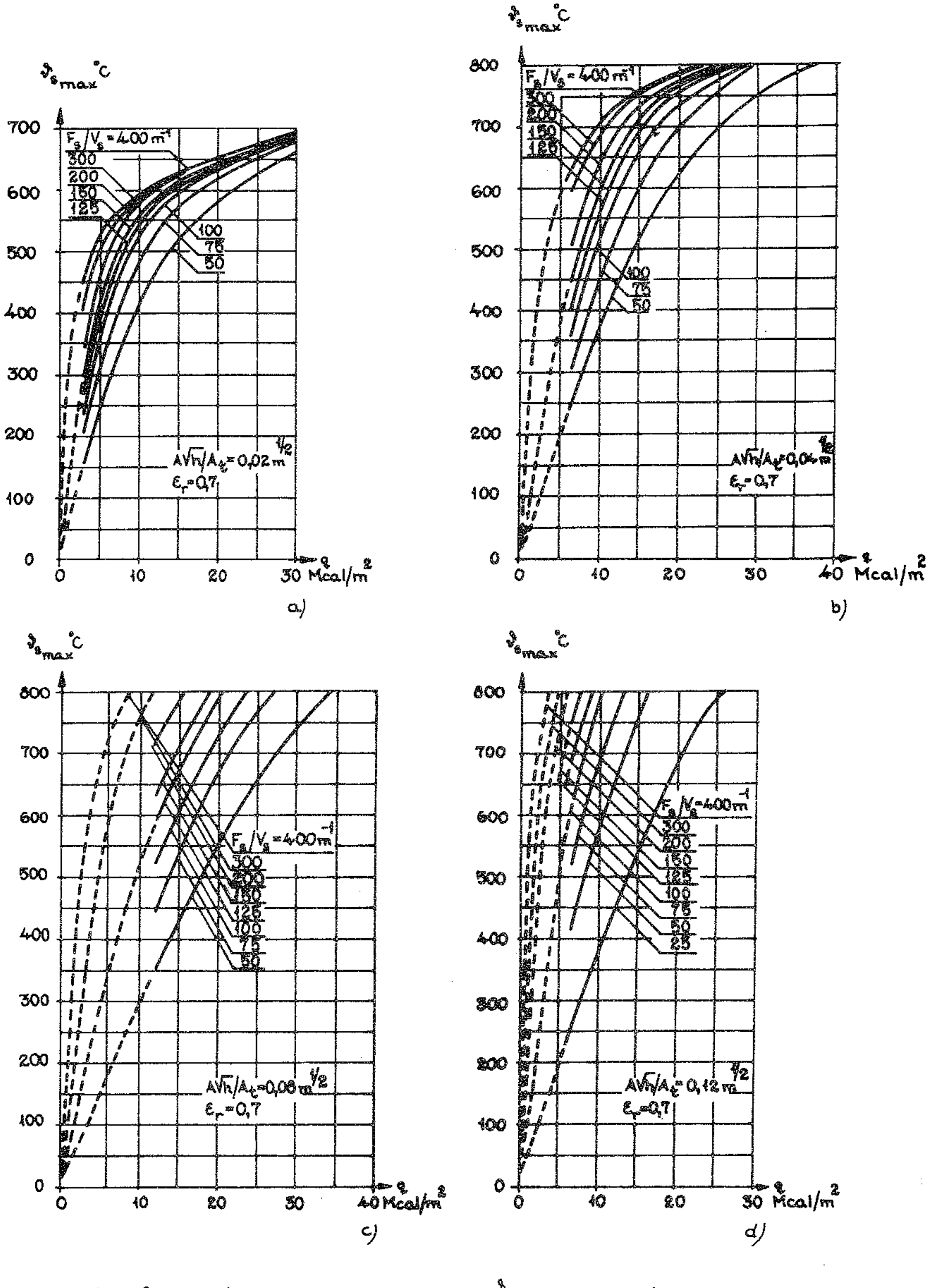


Fig. 8. Maximum steel temperature $\vartheta_{s_{max}}$ for a fire exposed, non--insulated steel structure at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient F_s/V_s. $\varepsilon_r = 0.7$. The curves are based on fire characteristics according to Fig. 6 with the influence of the cooling phase taken into account [12], [13]

Limpet spray asbestos (γ = 200 kg/m³)

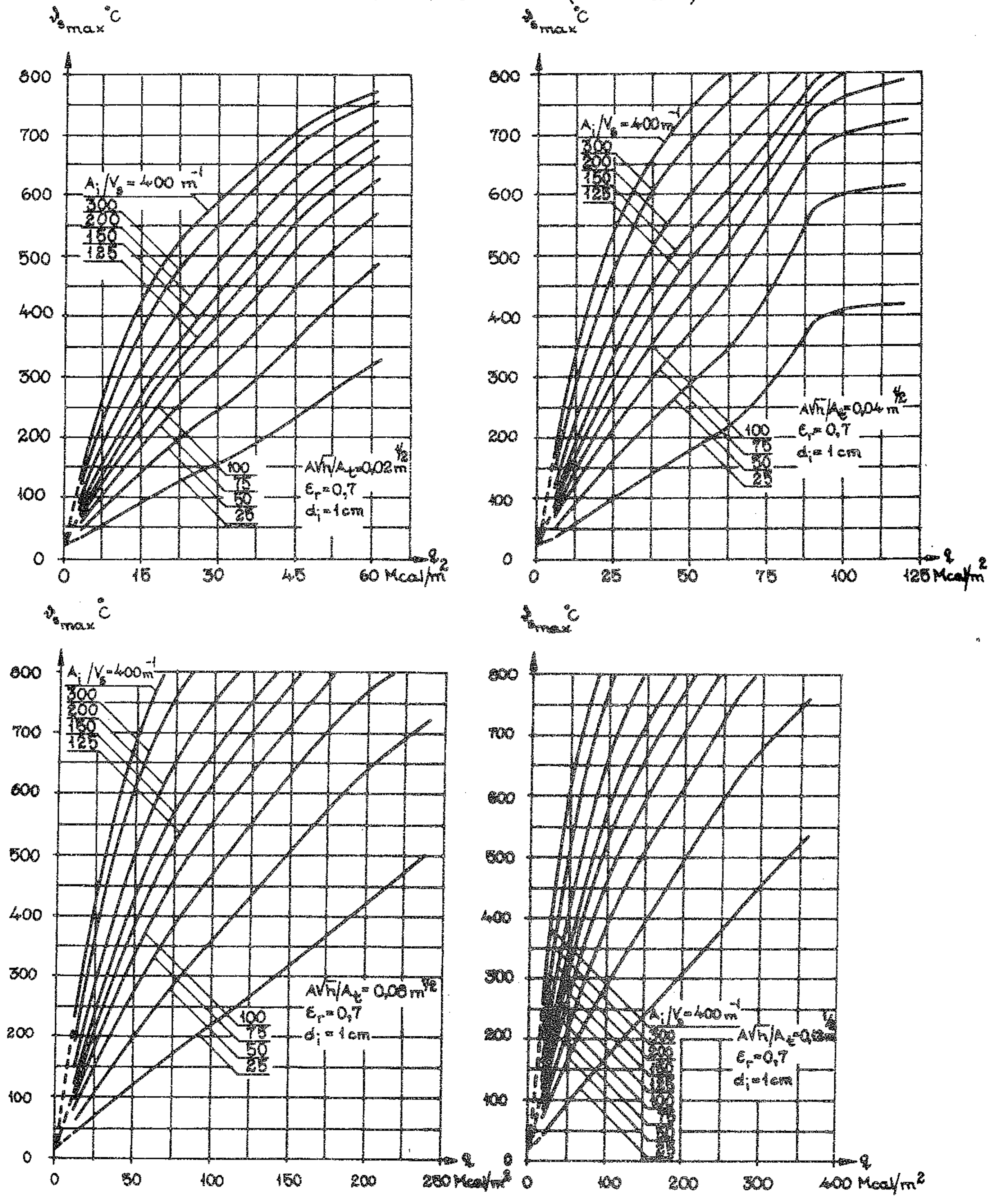


Fig. 9. Maximum steel temperature $\vartheta_{s_{max}}$ for a steel structure, insulated with 1 cm Limpet spray asbestos (γ = 200 kg/m³) and exposed to a fire at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient A_i/V_s. ε_r = 0.7. The curves are based on fire characteristics according to Fig. 6 with the influence of the cooling phase taken into account [13]

Analogously, the design diagrams reproduced in Fig. 9 [13] directly give the maximum steel temperature $\vartheta_{s_{max}}$ for a steel structure insulated with 1 cm Limpet spray asbestos, exposed to fire at varying opening factor $A\sqrt{h}/A_t$, fire load q, and relationship A_i/V_s. A_i then is the mean jacket surface of the insulation per unit length of the structure.

Pyrodur (γ = 315 kg/m^3)

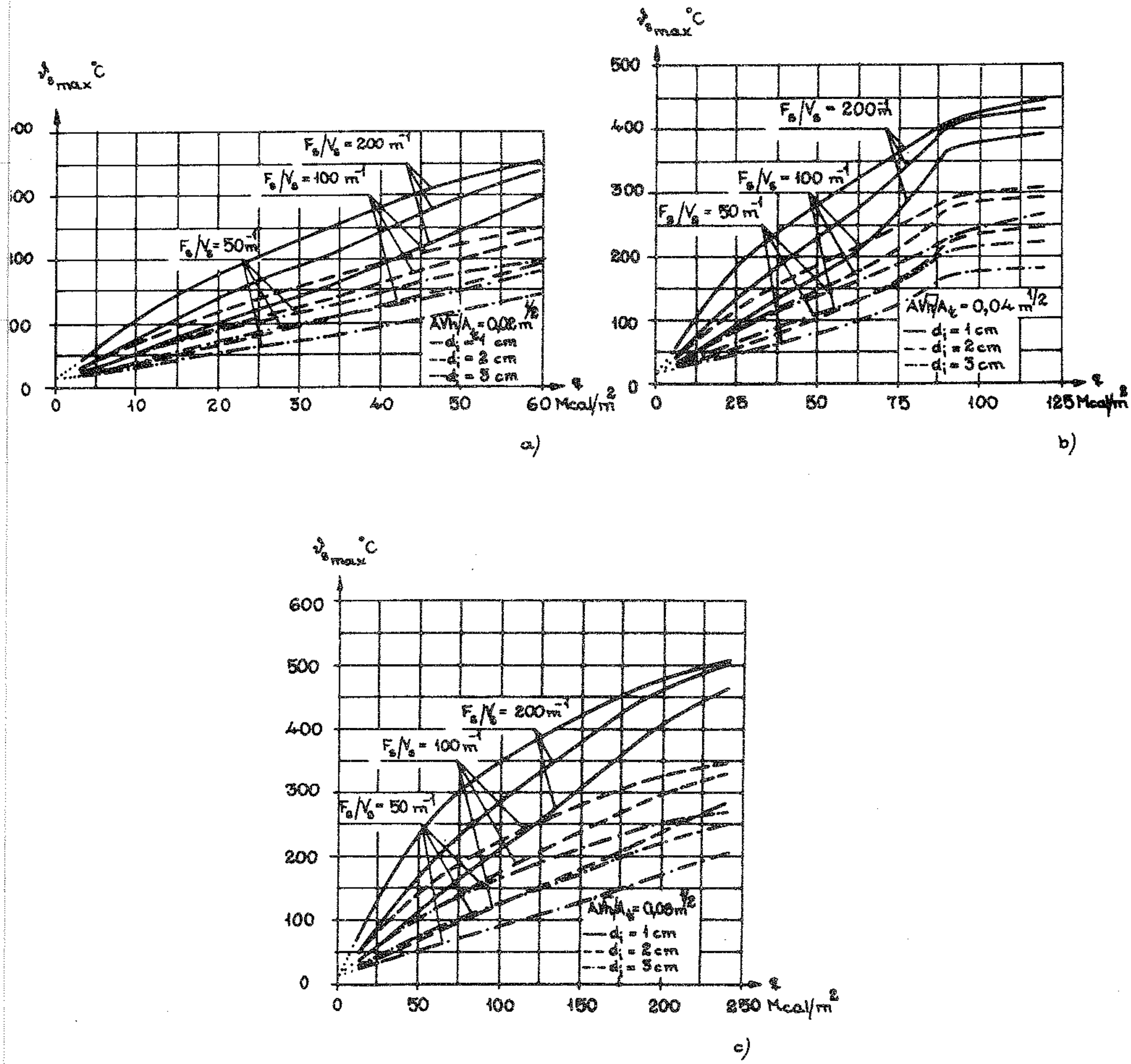


Fig. 10a-c

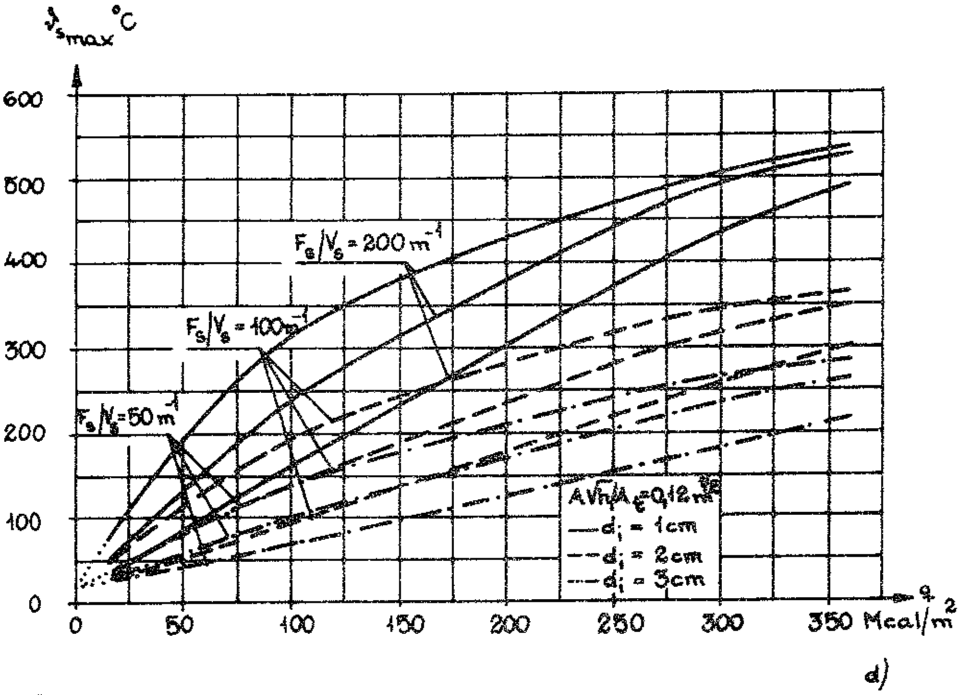


Fig. 10. Ceiling structure, composed of a reinforced concrete slab, load-bearing steel beams and an underlying insulation of Vermiculite plaster Pyrodur (γ = 315 kg/m^3). Maximum steel temperature $\vartheta_{s_{max}}$ for the steel beams of the structure, exposed to a fire from below at varying opening factor $A\sqrt{h}/A_t$, fire load q, quotient F_s/V_s, and insulation thickness d_i. The curves are based on fire characteristics according to Fig. 6 with the influence of the cooling phase taken into account [13]

Fig. 10 [13] illustrates the corresponding temperature conditions for a ceiling structure, composed of a reinforced concrete slab, load-bearing steel beams and an underlying insulation of Vermiculite plaster Pyrodur, fire exposed from below. The figure shows the maximum steel temperature $\vartheta_{s_{max}}$ for the steel beams of the structure at varying opening factor $A\sqrt{h}/A_t$, fire load q, quotient F_s/V_s, and insulation thickness d_i.

In Fig. 11 [13] the insulating properties are elucidated for a separating steel structure, composed of a non-load-bearing steel frame insulated on both sides by two gypsum plates with an individual thickness of 13 mm. The design diagram gives the maximum temperature $\vartheta_{v_{max}}$ of the unexposed face of the structure, when fire exposed on one side, at varying opening factor $A\sqrt{h}/A_t$ and fire load q. The curves have been calculated by a numerical data processing which takes into account the effect of the disintegration of a gypsum plate at a certain temperature condition.

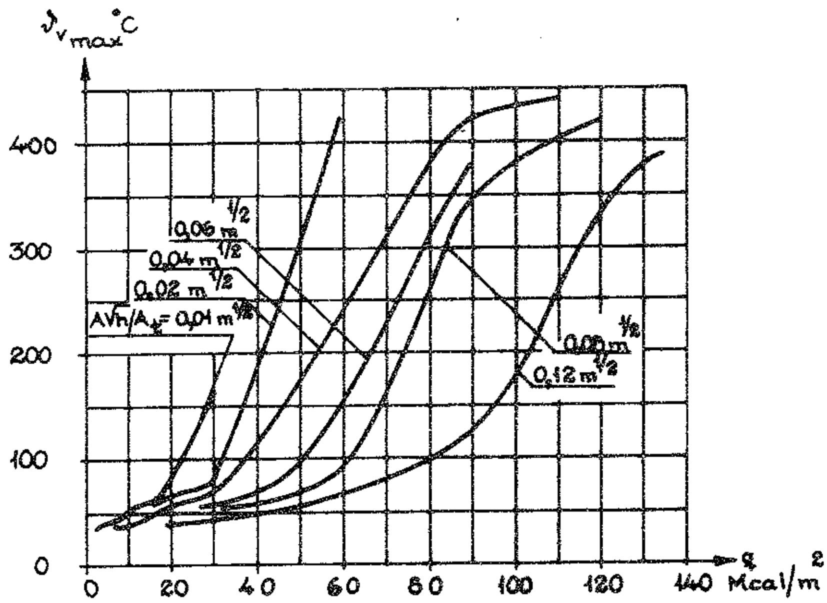
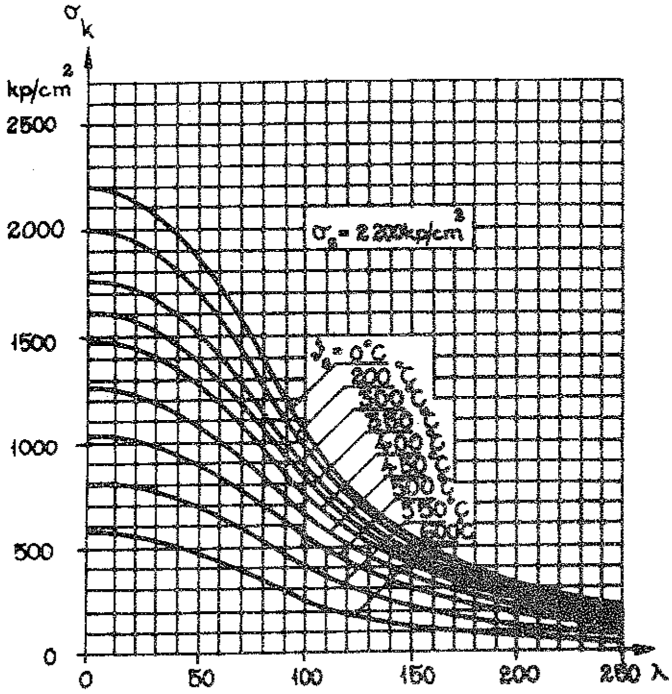
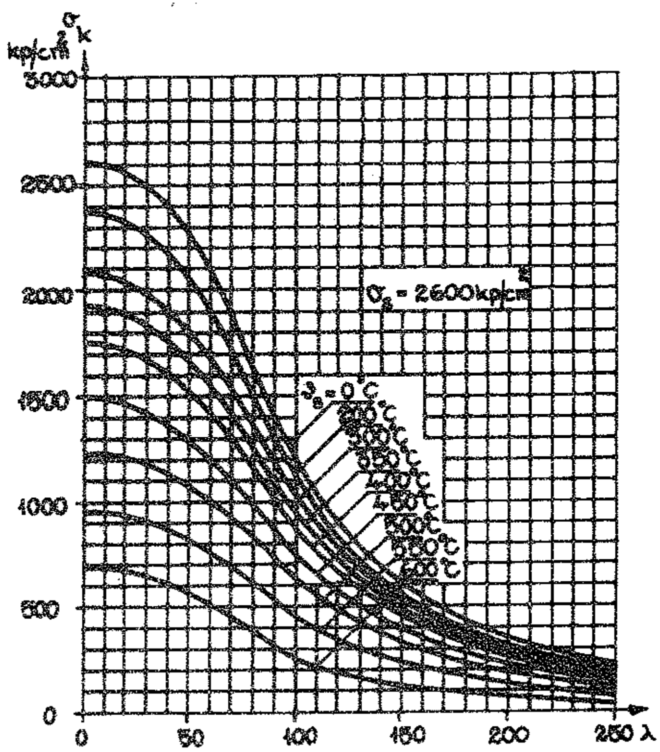


Fig. 11. Separating structure, composed of a non-load-bearing steel frame, insulated on both sides by two gypsum plates with an individual thickness of 13 mm. Maximum temperature of the unexposed face of the wall structure $\vartheta_{v_{max}}$, when exposed to a fire on one side, at varying opening factor $A\sqrt{h}/A_t$ and fire load q. The curves are based on fire characteristics according to Fig. 6 with the influence of the cooling phase taken into account [13]

Further examples of design diagrams for a differentiated fire engineering design of steel structures are shown in Figs. 12 and 13, as concerns a calculation of the load-bearing capacity or the time of fire resistance. The curves in Fig. 12 [12], [13] then present the variation with the steel temperature ϑ_s of the relationship between the buckling stress σ_k and the slenderness ratio λ for axially compressed columns made of steel having a yield point stress at room temperature σ_s = 2200, 2600 and 3200 kp/cm^2, respectively. The curves have been theoretically determined on the basis of data on the change of the 0.2 stress σ_s and the modulus of elasticity E with the temperature ϑ_s for mild structural steel, received in tensile tests at a very slow loading velocity, which implies that some effect of short-time creep is considered [14]. The curves are valid under the presumption that the columns are unrestrained with respect to longitudinal expansion during the fire. A complementary illustration of the influence on the buckling stress σ_k of a partial restraint to longitudinal expansion is given by Fig. 13 [15] for an axially compressed steel column with a slenderness ratio $\lambda = 100$ and a quotient $i/d = 1$, where $i =$ = the radius of gyration and d = the distance from the gravity centre axis to the edge of the section with maximum compressive stress.





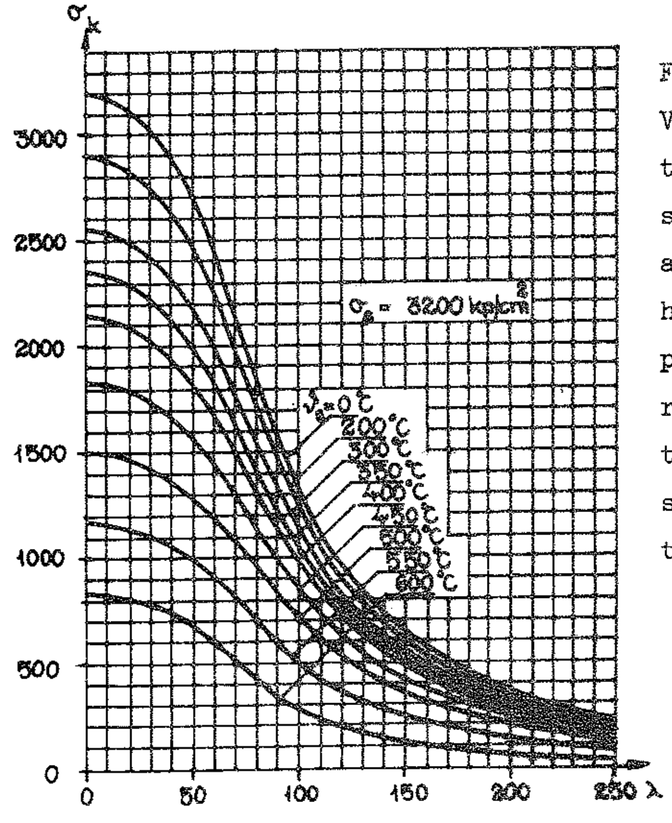


Fig. 12.
Variation with the steel temperature ϑ_s of the relationship between the buckling stress σ_k and the slenderness ratio λ for axially compressed columns made of steel having a yield point stress at room temperature σ_s = 2200, 2600 and 3200 kp/cm^2, respectively. The curves are applicable to columns which are unrestrained with respect to longitudinal expansion during the fire [12], [13]

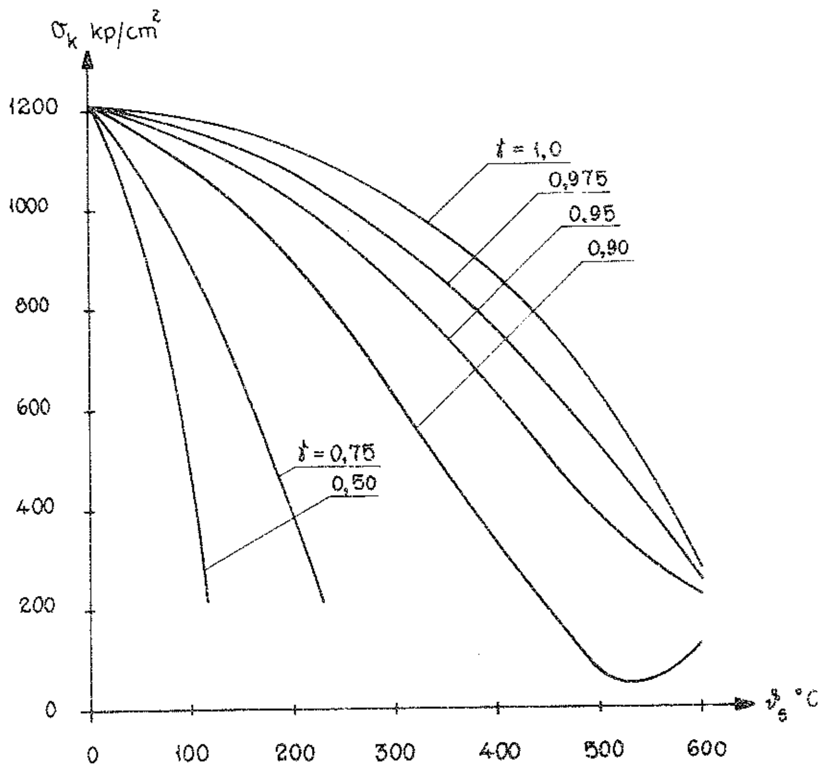


Fig. 13

Fig. 13. Effect on the buckling stress σ_k of a partial restraint to longitudinal expansion for a fire exposed, axially compressed steel column with a slenderness ratio $\lambda = 100$ and a quotient $i/d = 1$. γ defines the degree of axial restraint as the ratio between the possible longitudinal expansion and the completely free elongation of the column [15]

The degree of axial restraint is characterized by the coefficient γ, giving the quotient between the possible longitudinal expansion and the completely free elongation of the fire exposed column. Accordingly, $\gamma = 1$ corresponds to no longitudinal restraint at all, and $\gamma = 0$ to a full restraint to axial expansion of the column.

As a final example of design diagrams, suitable for a differentiated structural fire engineering design procedure of the type summary described, Fig. 14 [16] gives the relationship between the allowed fire load q_{allow}, the width of the cross section b and the distance t from the layer of the reinforcement to the underneath side of a rectangular, reinforced concrete beam, exposed to a fire on three sides. The results refer to a critical temperature of the reinforcement $\vartheta_s = 510^{\circ}C$ and have been calculated on the basis of fire characteristics for a compartment with the opening factor $A\sqrt{h}/A_t = 0.04\ m^{1/2}$ according to Fig. 6 with the influence of the cooling phase taken into account. The applicability of the results are marked in the diagram by horizontal arrows, connected to the ratio ν between the width b and the height h of the cross section.

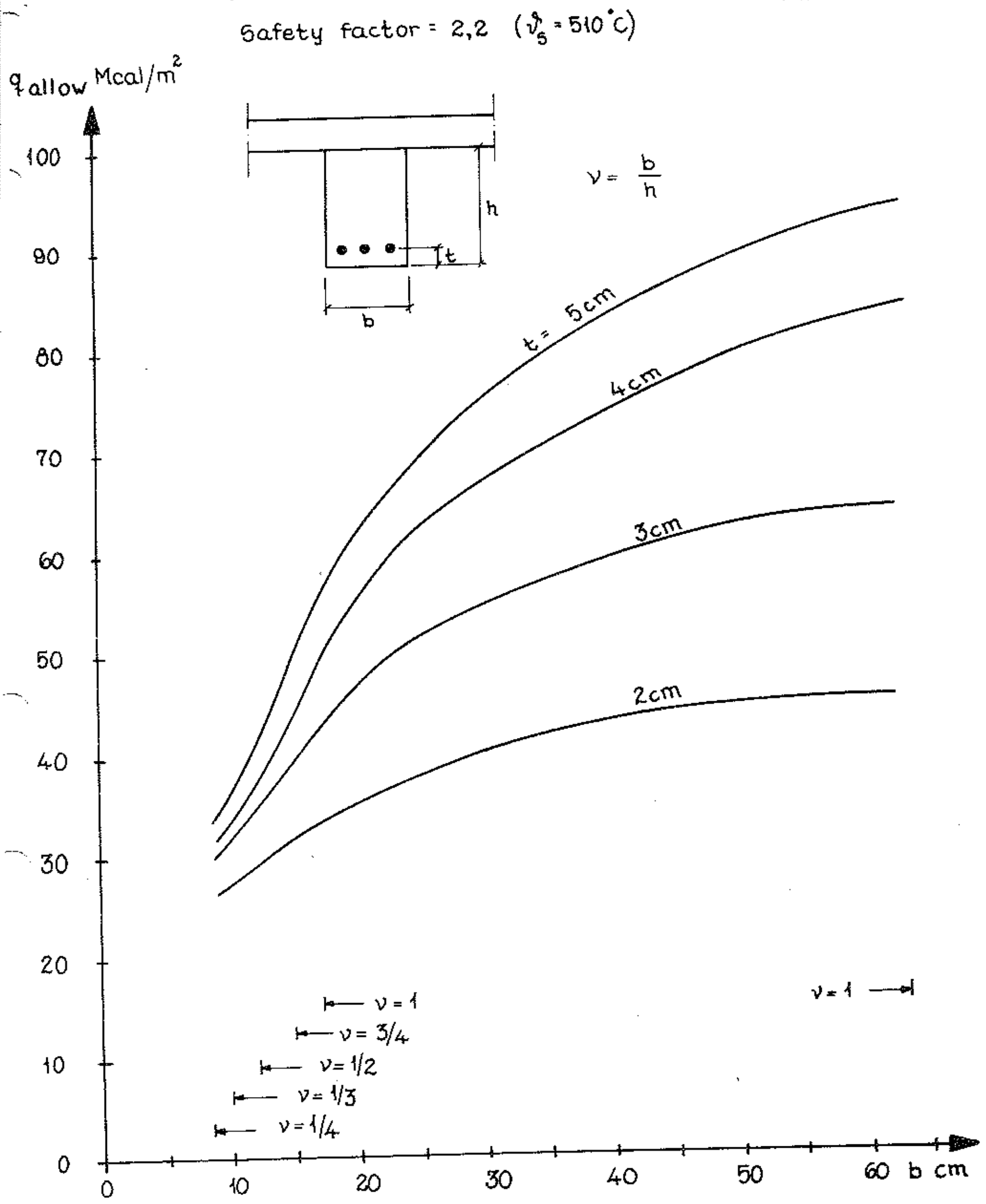


Fig. 14

Fig. 14
Rectangular reinforced concrete beam, exposed to a fire on three sides. Relationship between the allowed fire load q_{allow}, the width of the cross section b and the distance t from the layer of the reinforcement to the underneath side of the cross section. Critical temperature of the reinforcement $\vartheta_s = 510^{\circ}C$. The curves are based on fire characteristics according to Fig. 6 with the influence of the cooling phase taken into account [16]

Summarized, a structural fire engineering design, directly based on differentiated gastemperature-time curves, according to the above is characterized by mainly a theoretical design procedure. The applicability in practice of this procedure, essentially can be facilitated by design diagrams, calculated for different types of structures or structural elements by means of computers. The design procedure is not connected to any need of classifications and gives a low priority to the present standard fire resistance test of elements of building construction. In the design procedure, the results of such standard tests can be used either for a confirmation, point by point, of the theoretical treatment or for getting basic informations, necessary for the calculations. In those cases, when these basic informations depend on the detail characteristics of the process of fire development - for instance, basic data concerning the disintegration of structural materials, enlarged short-time effect of creep and shrinkage, effect of crack formation and spalling, behaviour and strength of fastening devices for different types of insulation, rate of increase in the depth of the charred layer at timber structures - the design procedure can necessitate experimental investigations at gastemperature-time curves diverging from the standard time--temperature curve. In most cases, the data required then can be determined by essentially less extensive experiments than the standard fire resistance test.

3.2 Differentiated structural fire engineering design, based on a fictitious time of fire duration

An alternative way of taking into account the effect of varying fire development characteristics in a structural fire engineering design, put forward in the literature [8], [17] and in the current discussion, is based on a fictitious time of fire duration connected to the standard time-temperature curve.

In principle, the conception fictitious time of fire duration T_f can be defined according to Fig. 15, giving an examplification for a fire exposed non-insulated steel structure. The figure shows by the full-line curves the time-variation of the gastemperature ϑ_t and the steel temperature ϑ_s corresponding to a real fire action, determined by the fire load q, the opening factor $A\sqrt{h}/A_t$, and the thermal properties of the structures bounding the compartment. The dash-line curves give the standard time-temperature variation ϑ_t (S.C.) and the appurtenant time-curve of the temperature ϑ_s (S.C.) of the steel structure. A transfer of the maximum steel temperature $\vartheta_{s_{max}}$ for the real fire action to the curve ϑ_s (S.C.), belonging to the standard time-temperature curve, determines the fictitious time of fire duration T_f.

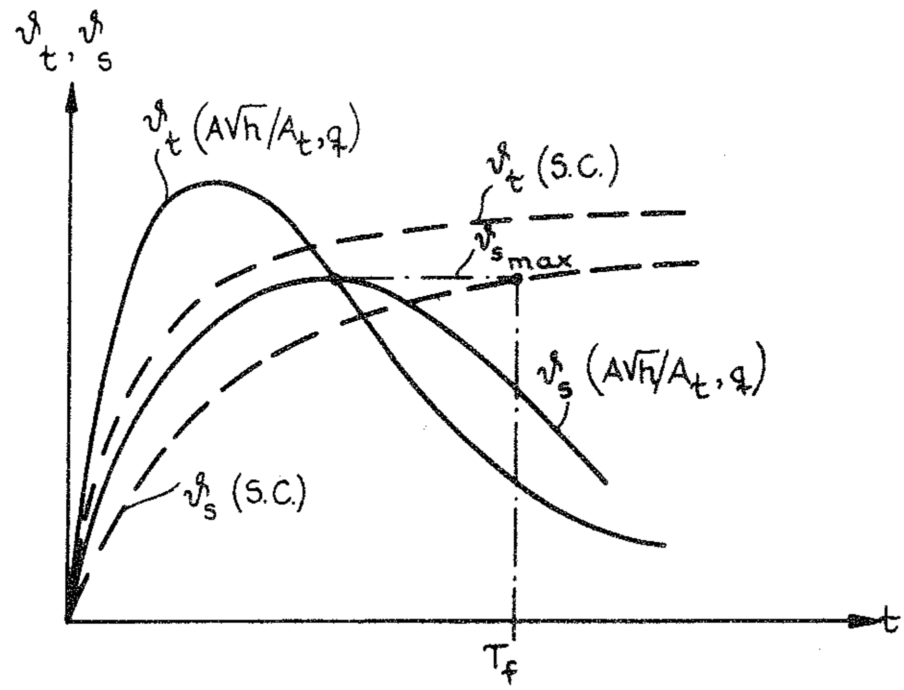


Fig. 15. The principle of evaluating the fictitious time of fire duration T_f, examplified for a fire exposed, non-insulated steel structure. The full-line curves refer the gas-temperature ϑ_t and the steel temperature ϑ_s for a real fire action, characterized by the opening factor $A\sqrt{h}/A_t$ and the fire load q. The dash-line curves give the corresponding temperatures at a fire exposure according to the standard time-temperature curve (S.C.)

A slightly modified way of defining the fictitious time of fire duration T_f has been presented by Margaret Law [17] with special application to fire exposed insulated steel structures. Among elements of construction with varying thermal characteristics with respect to fire exposure that element is chosen, which for a given gastemperature-time curve of a real fire development gets a maximum steel temperature of a fixed value. T_f is then determined over the standard time-temperature curve for the same element and the same steel temperature. By repeating this procedure for different characteristics of real fires, a diagram can be constructed, applicable to a rough determination of a fictitious time of fire duration T_f for an insulated steel structure, irrespective of the detail properties of the structure.

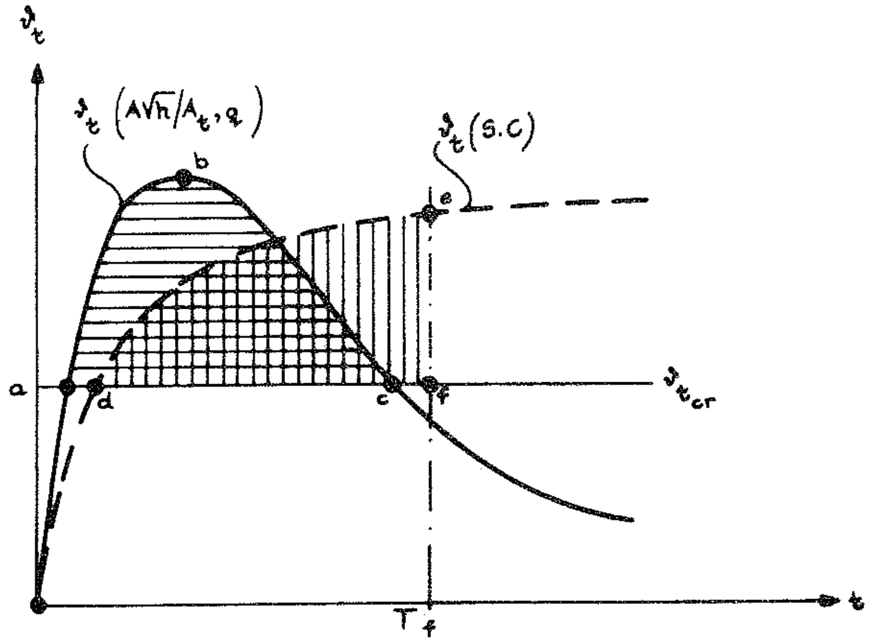


Fig. 16. Fictitious time of fire duration T_f, defined according to Kawagoe and Sekine [8]. The full-line curve refers the gastemperature ϑ_t for a real fire action and the dash-line curve the gastemperature according to the standard fire resistance test (S.C.). T_f is given by the condition that area (a - b - c) = area (d - e - f) with $\vartheta_{t_{cr}}$ = a critical temperature with respect to the fire behaviour of the actural structure

A third alternative of introducing the conception fictitious time of fire duration T_f has been put forward by Kawagoe and Sekine [8]. In principle, their definition of T_f is illustrated by Fig. 16, which shows by the full-line curve the time-variation of the gastemperature ϑ_t corresponding to a real fire with a fire load q and an opening factor $A\sqrt{h}/A_t$ and by the dash-line curve the standard time-temperature variation ϑ_t (S.C.). For a given type of structure a temperature level $\vartheta_{t_{cr}}$ is chosen, which is critical with respect to the fire behaviour of the structure, and T_f is then defined by a condition, saying that the two areas between the respective gastemperature-time curves and the temperature level $\vartheta_{t_{cr}}$ are to be equal.

Going back to the fictitious time of fire duration T_f, defined according to Fig. 15, it is evident from a functional point of view that T_f, given as determined by the fire load q and the opening factor $A\sqrt{h}/A_t$, commonly must depend on a great number of structural influences - for an insulated steel structure: the insulation material, the thickness of the insulation, the quotient A_i/V_s, and the resultant emissivity ε_r; for a reinforced concrete beam of rectangular cross section: the height h and the width b of the cross section, the distance t from the layer of reinforcement to a fire exposed surface, and the resultant emissivity ε_r. For an examplifying illustration of the importance of such structural influences, some calculations [1] have been carried out for different types of structures of the fictitious time of fire duration under the assumption, that the real fire development is characterized by gastemperature-time curves according to Fig. 6. The results of these calculations are presented in Figs. 17 to 26.

By the curves in Fig. 17 then is illustrated the variation of the fictitious time of fire duration T_f with the quotient F_s/V_s for a non-insulated steel structure. For the same type of structure with given characteristics, Fig. 18 complementary illustrates the influence on T_f of varying resultant emissivity ε_r, as concerns the fire action according to the standard time-temperature curve. This problem is essential of the reason, mentioned above, that the radiation and convection characteristics in standard fire resistance tests can vary considerably from one furnace to another, depending on the detail design of the furnace and the type of fuel.

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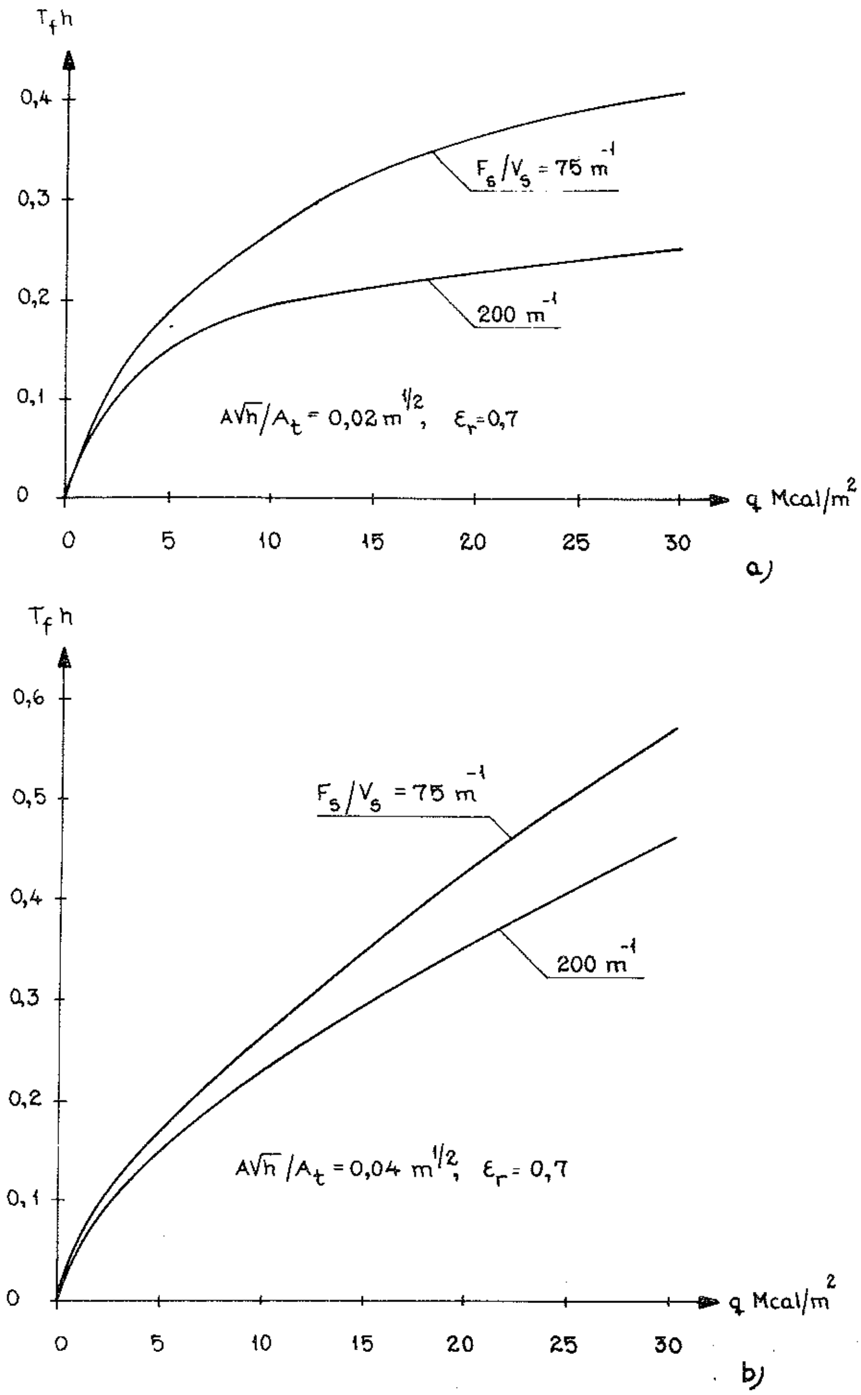
[1] These calculations have been made by Sven Erik Magnusson, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Lund



$T_f h$
0,4
0,3
0,2
0,1
0
$F_s/V_s = 75\ m^{-1}$
$200\ m^{-1}$
$A\sqrt{h}/A_t = 0{,}02\ m^{1/2}$, $\varepsilon_r = 0{,}7$
0 5 10 15 20 25 30
q Mcal/m²
a)
$T_f h$
0,6
0,5
0,4
0,3
0,2
0,1
0
$F_s/V_s = 75\ m^{-1}$
$200\ m^{-1}$
$A\sqrt{h}/A_t = 0{,}04\ m^{1/2}$, $\varepsilon_r = 0{,}7$
0 5 10 15 20 25 30
q Mcal/m²
b)

Fig. 17a-b

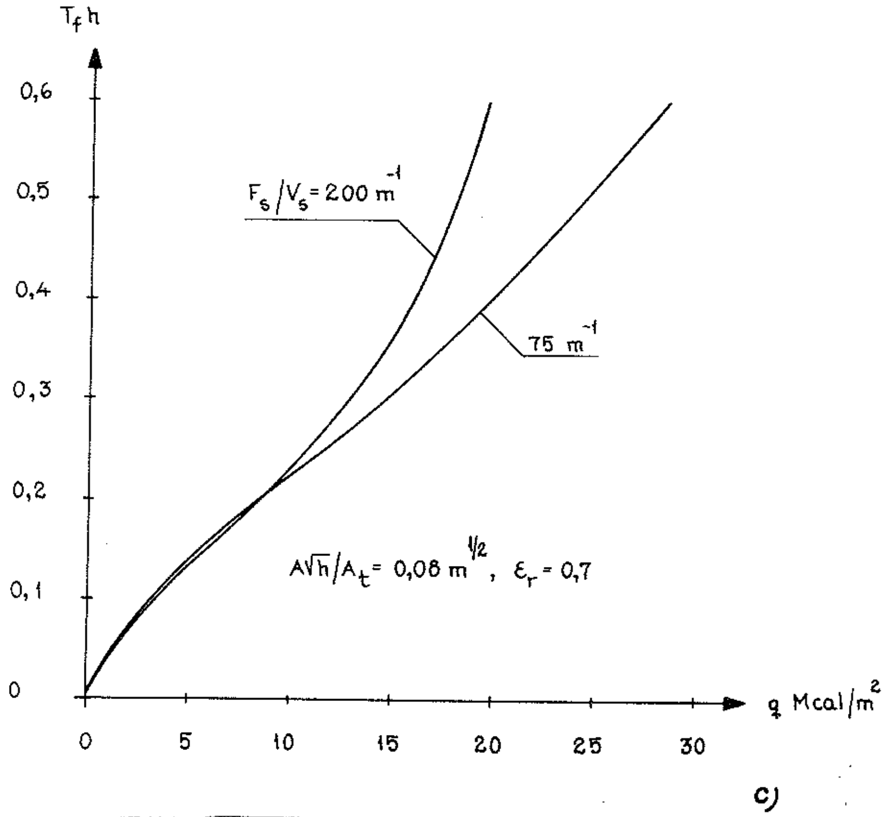


Fig. 17. Fictitious time of fire duration T_f for a fire exposed, non-insulated steel structure at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient F_s/V_s. Resultant emissivity ε_r = 0.7

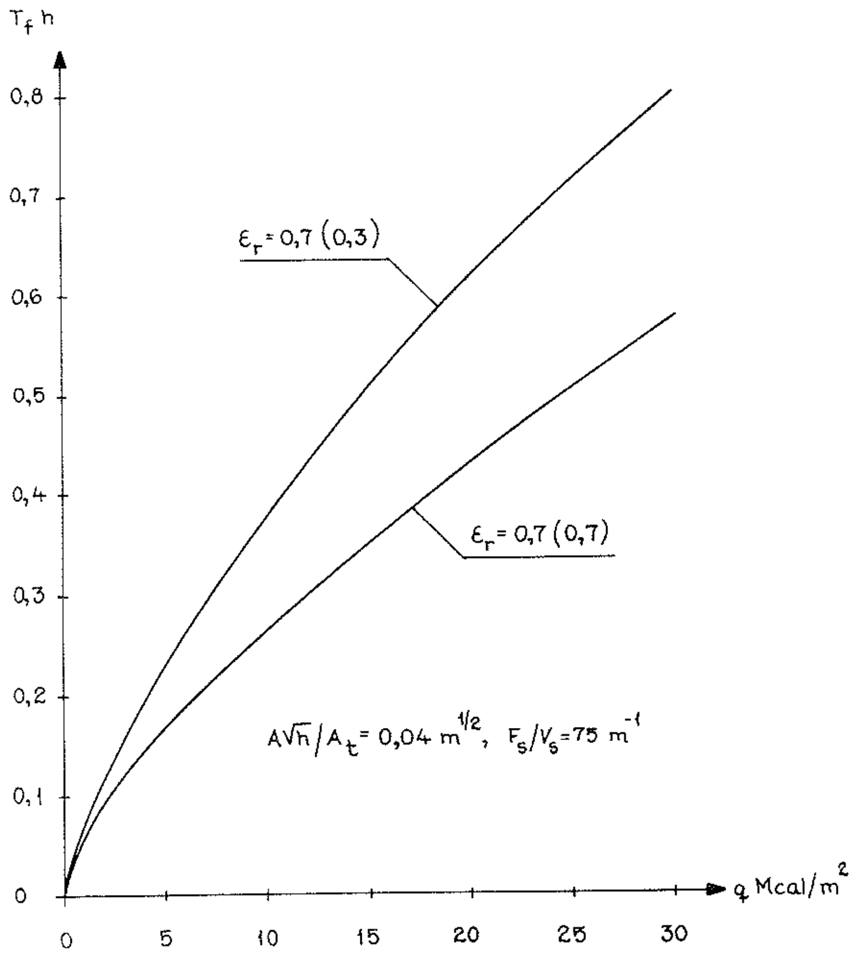
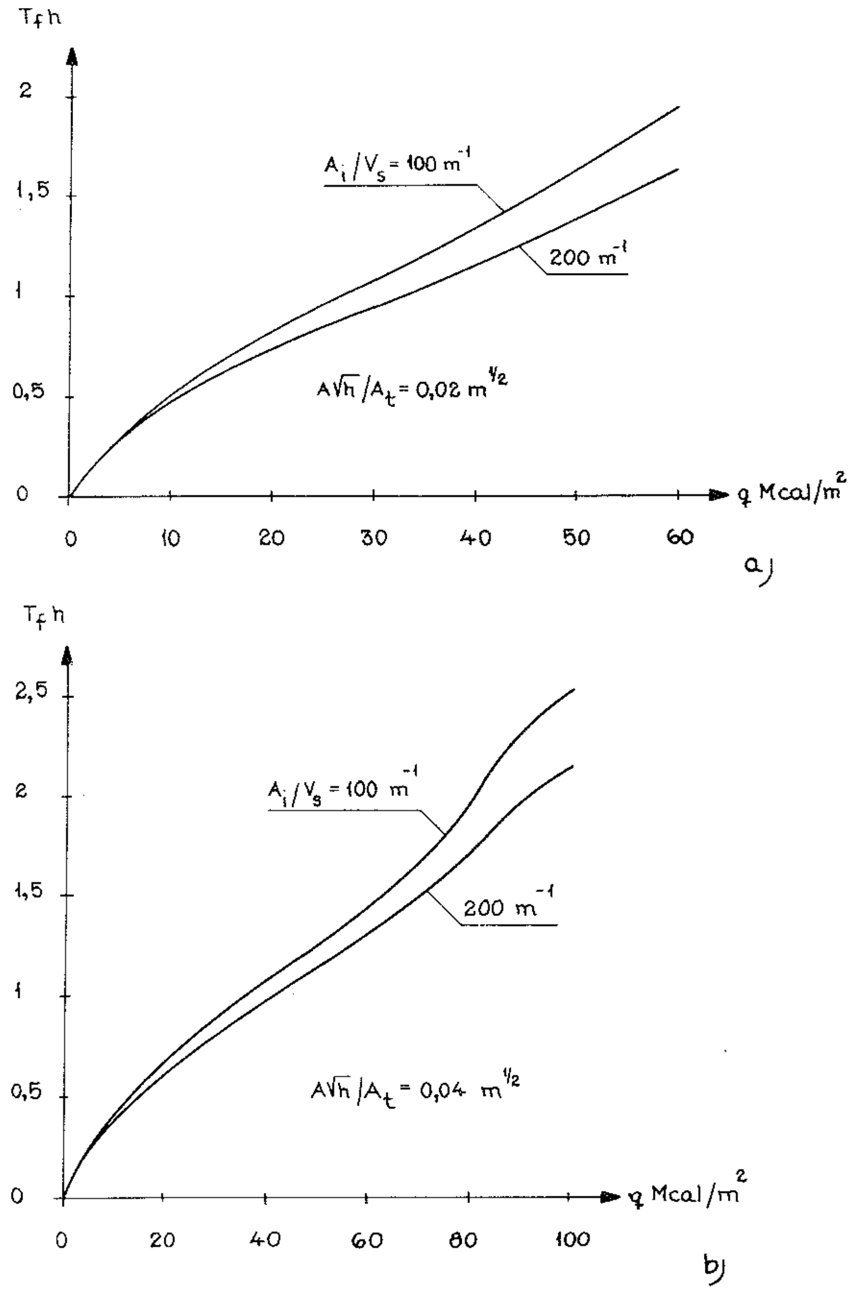


Fig. 18. Fictitious time of fire duration T_f at varying fire load q for a fire exposed, non-insulated steel structure. $A\sqrt{h}/A_t = 0.04\ m^{1/2}$, $F_s/V_s = 75\ m^{-1}$. Both curves refer to a real fire exposure with a resultant emissivity $\varepsilon_r = 0.7$. As concerns the corresponding fire action according to the standard time-temperature curve, the upper curve presupposes a resultant emissivity $\varepsilon_r = 0.3$ and the lower curve a resultant emissivity $\varepsilon_r = 0.7$

Together, Figs. 19, 20 and 21 examplify the influence on T_f of variations in the type of insulation, the thickness of insulation and the quotient A_i/V_s for a fire exposed insulated steel structure. Fig. 19 then applies to a 2 cm insulation of Limpet spray asbestos, while Figs. 20 and 21 refer to an insulation of one or two 13 mm gypsum plates, i.e. a product, which is disintegrated at a certain temperature condition.



$T_f h$
2
1,5
1
0,5
0
0
10
20
30
40
50
60
q Mcal/m²
$A_i/V_s = 100\ m^{-1}$
200 m⁻¹
$A\sqrt{h}/A_t = 0,02\ m^{1/2}$
a)
$T_f h$
2,5
2
1,5
1
0,5
0
0
20
40
60
80
100
q Mcal/m²
$A_i/V_s = 100\ m^{-1}$
200 m⁻¹
$A\sqrt{h}/A_t = 0,04\ m^{1/2}$
b)

Fig. 19a-b

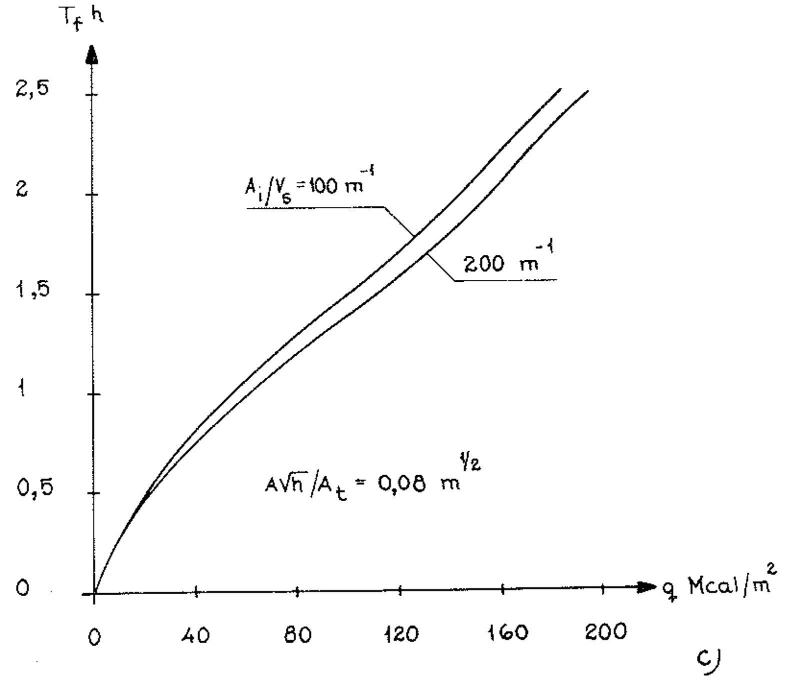


Fig. 19. Fictitious time of fire duration T_f for a fire exposed steel structure, insulated by 2 cm Limpet spray asbestos (γ = 200 kg/m³), at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient A_i/V_s. Resultant emissivity $\varepsilon_r = 0.7$

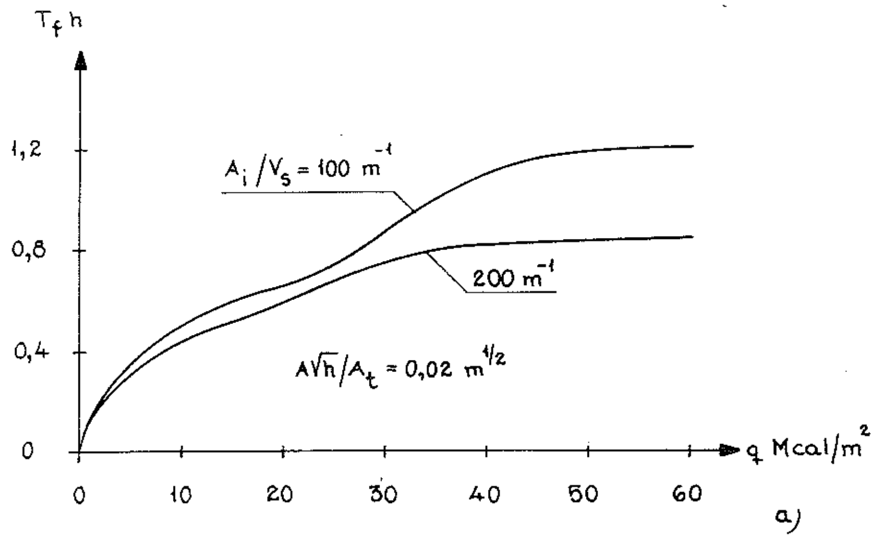


Fig. 20a

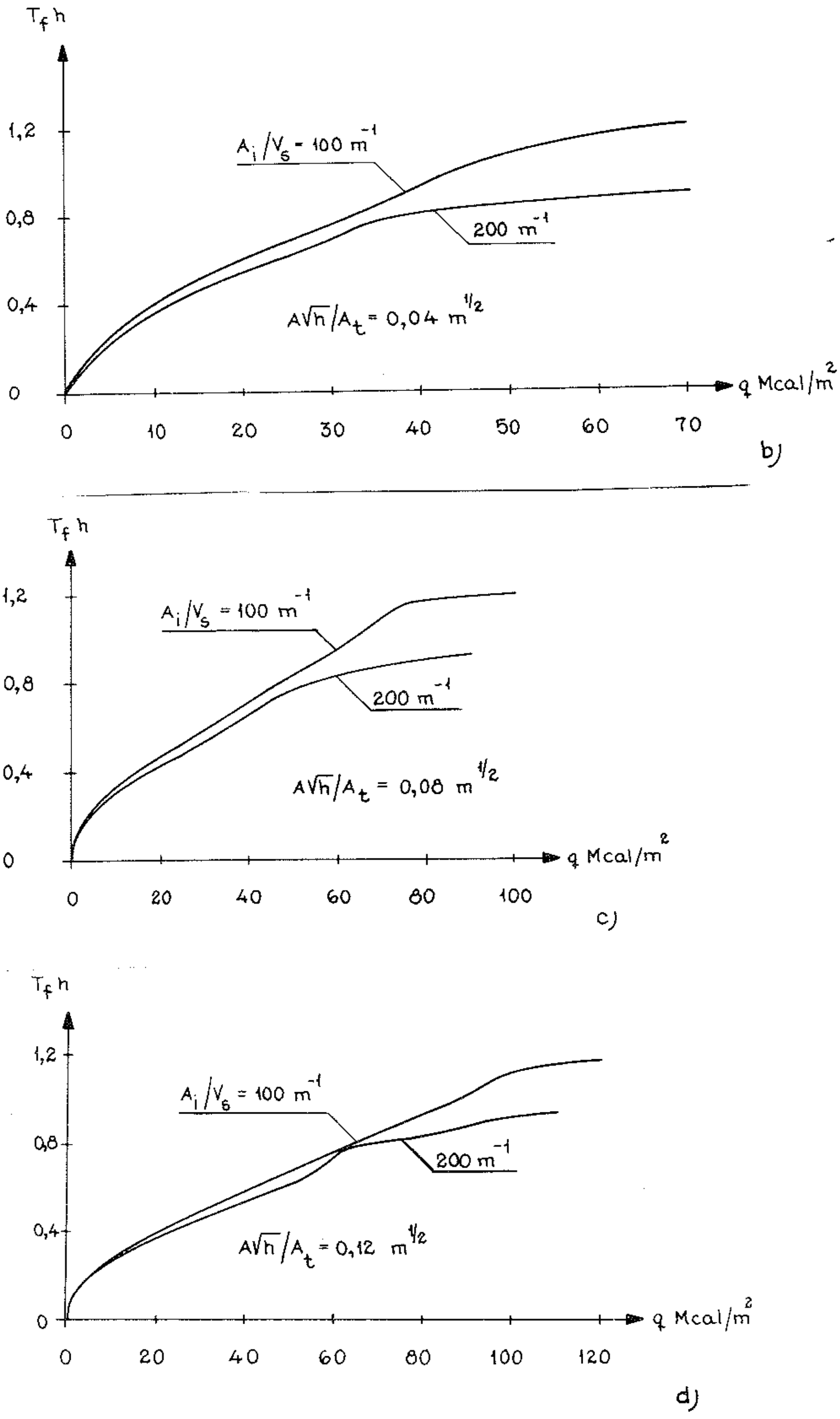


Fig. 20. Fictitious time of fire duration T_f for a fire exposed steel structure, insulated by a 13 mm gypsum plate, at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient A_i/V_s. Resultant emissivity $\varepsilon_r = 0.7$

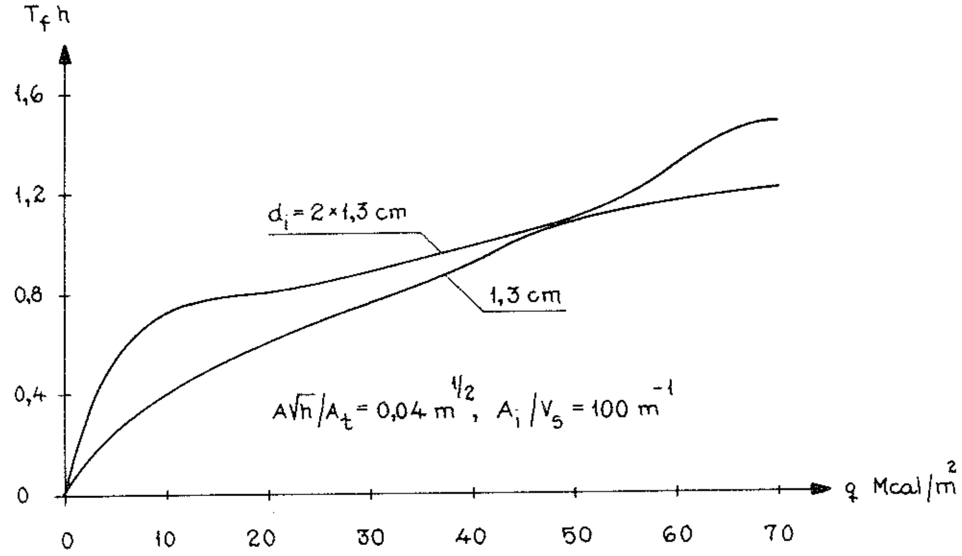


Fig. 21. Fictitious time of fire duration T_f at varying fire load q for a fire exposed steel structure, insulated with one and two 13 mm gypsum plates, respectively. $A\sqrt{h}/A_t = 0.04\ m^{1/2}$, $A_i/V_s = 100\ m^{-1}$. Resultant emissivity $\varepsilon_r = 0.7$

Figs. 22 and 23, which are valid for a ceiling structure, composed of a reinforced concrete slab, load-bearing steel beams and an underlying insulation of the Vermiculite plaster Pyrodur, elucidate in combination the variation of T_f with the thickness of the insulation and the quotient F_s/V_s.

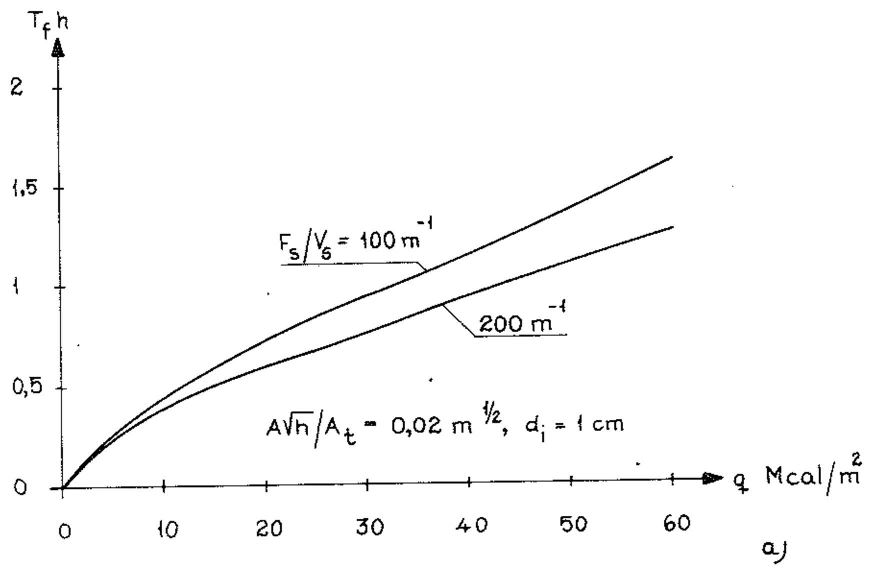


Fig. 22a

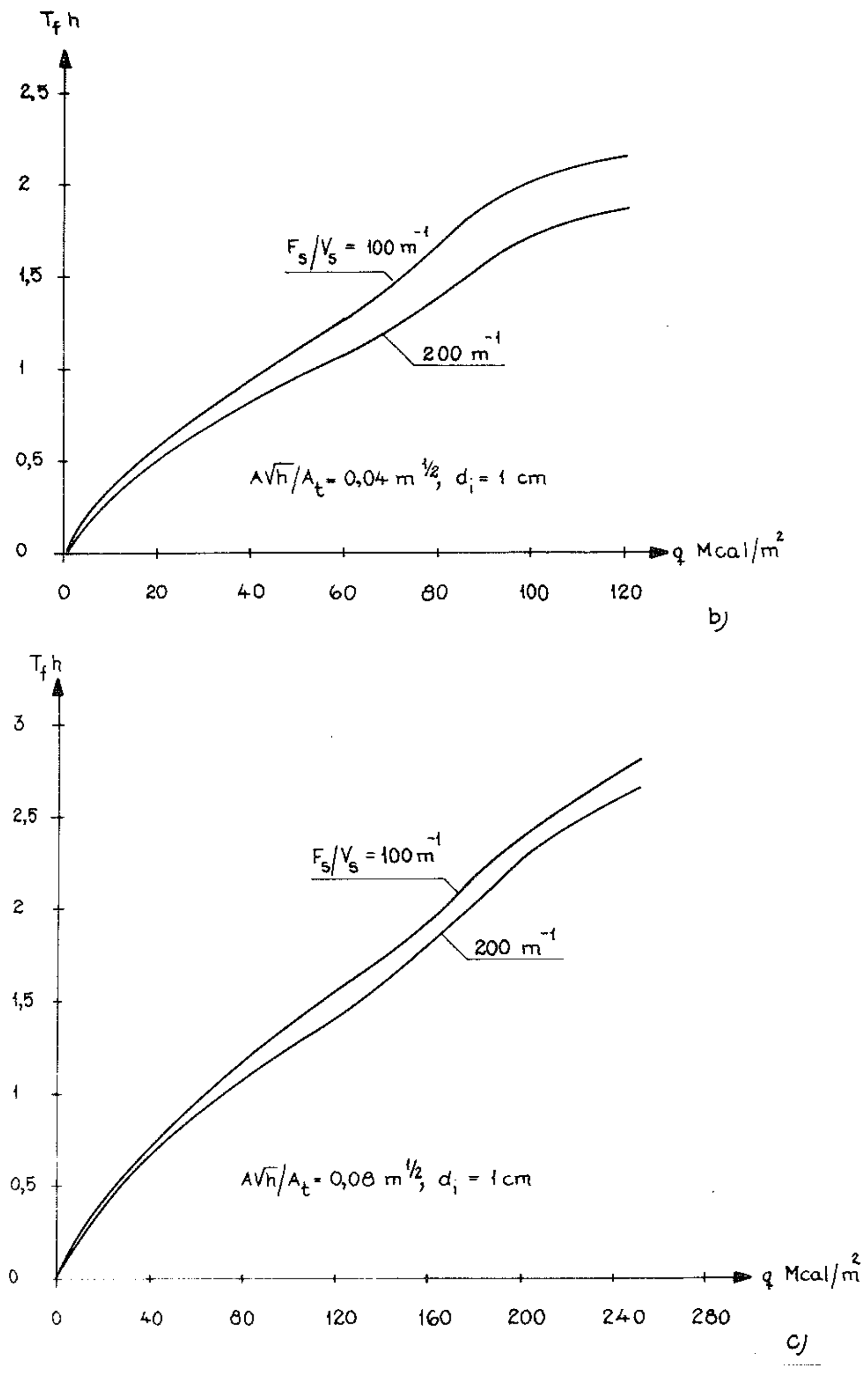


Fig. 22. Ceiling structure, composed of a 20 cm reinforced concrete slab, load-bearing steel beams, and an underlying insulation of 1 cm Vermiculite plaster Pyrodur (γ = 315 kg/m^3). Fictitious time of fire duration T_f for the structure, exposed to a fire from below, at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient F_s/V_s

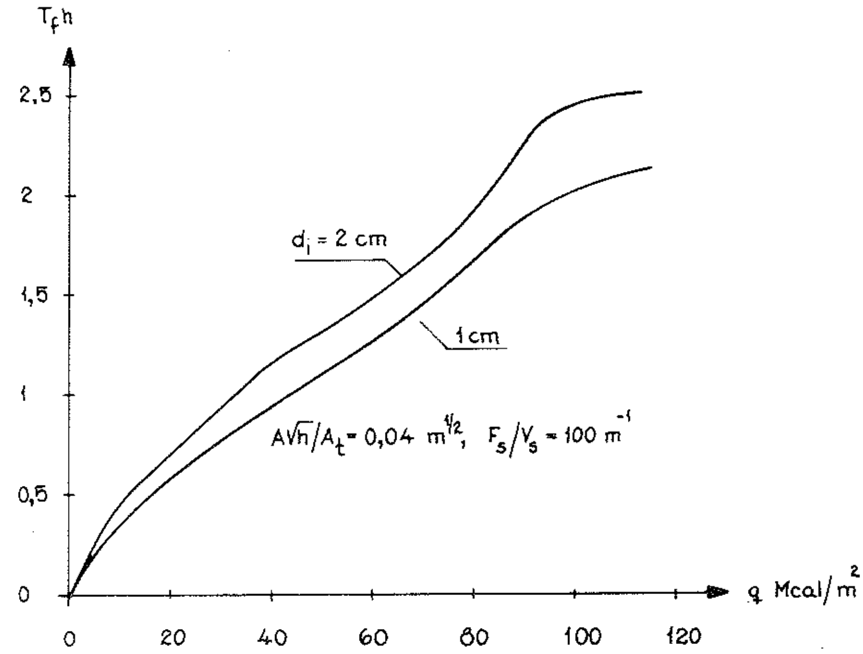


Fig. 23. Ceiling structure, composed of a 20 cm reinforced concrete slab, load-bearing steel beams, and an underlying insulation of 1 cm and 2 cm Vermiculite plaster Pyrodur (γ = 315 kg/m^3), respectively. Fictitious time of fire duration T_f for the structure, exposed to a fire from below, at varying fire load q. $A\sqrt{h}/A_t$ = 0.04 $m^{1/2}$, F_s/V_s = = 100 m^{-1}

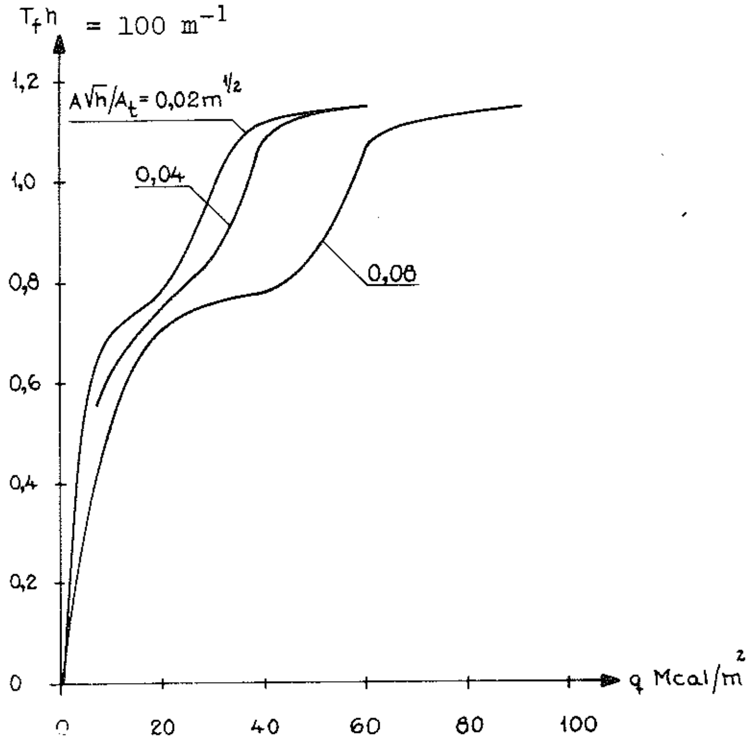


Fig. 24. Separating steel structure, composed of a non-load-bearing steel frame, insulated on both sides by two gypsum plates with an individual thickness of 13 mm. Fictitious time of fire duration T_f for the structure, exposed to a fire on one side, at varying opening factor $A\sqrt{h}/A_t$ and fire load q

Fig. 24 shows the fictitious time of fire duration T_f for a separating steel structure, composed of a non-load-bearing steel frame, insulated on both sides by two gypsum plates with an individual thickness of 13 mm.

Compared to each other, Figs. 17 to 24 for fire exposed steel structures illustrate the complex effect on T_f of variations in the structural design.

Finally, Figs. 25 and 26 demonstrate the influence on T_f of varying distance t from the layer of the reinforcement to the underneath side of a rectangular, reinforced concrete beam, exposed to a fire on three sides.

From the results presented in Figs. 17 to 24 the following conclusions can be drawn.

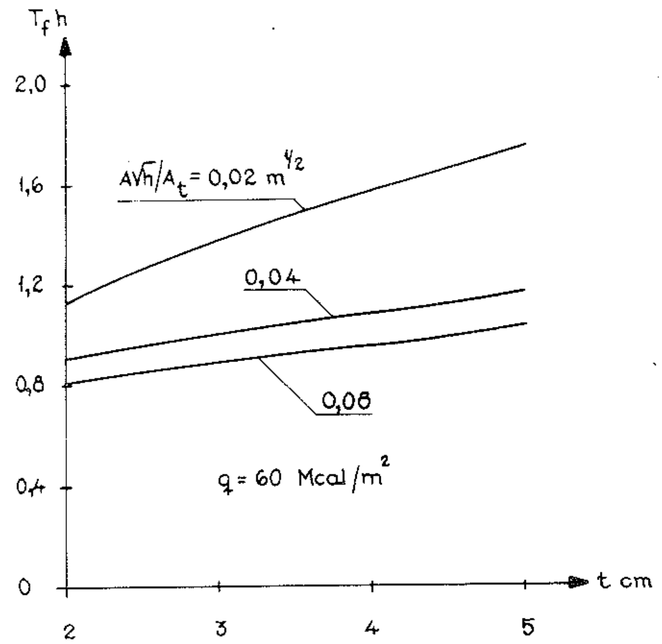


Fig. 25. Reinforced concrete beam of rectangular cross section with height h = 44.7 cm and width b = 22.4 cm, exposed to a fire on three sides. Fictitious time of fire duration T_f at varying opening factor $A\sqrt{h}/A_t$ and distance t from the layer of the reinforcement to the underneath side of the beam. Fire load q = 60 $Mcal/m^2$

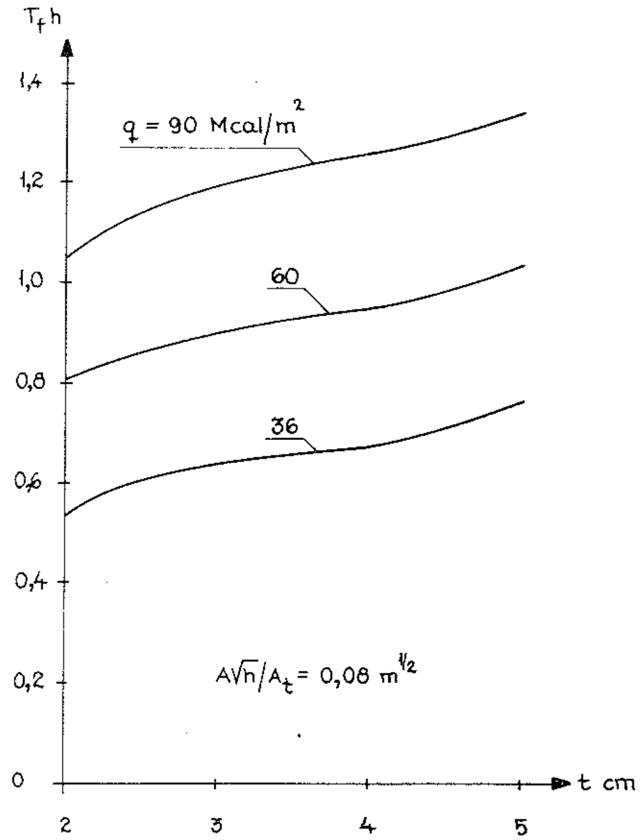


Fig. 26. Reinforced concrete beam of rectangular cross section with height h = 44.7 cm and width b = 22.4 cm, exposed to a fire on three sides. Fictitious time of fire duration T_f at varying fire load q and distance t from the layer of the reinforcement to the underneath side of the beam. Opening factor $A\sqrt{h}/A_t$ = 0.08 $m^{1/2}$

For a non-insulated steel structure the effect on the fictitious time of fire duration T_f of variations in the structural parameter F_s/V_s is considerable, especially for a fire development with a low value of the opening factor $A\sqrt{h}/A_t$. For an insulated steel structure, the corresponding effect - the influence of variations in the structural parameter A_i/V_s - is smaller. A change from a more resistant material of insulation to a material with disintegration properties then leads to an increased effect of variations in the parameter A_i/V_s whithin the temperature region above the first disintegration point of the insulation.

Differences in the radiation and convection characteristics of fire test furnaces can give rise to great variations in the fictitious time of fire duration T_f for non-insulated steel structures. For insulated steel structures the effect of such differences is less decisive.

From a summary comparison, based on the very fragmentary results presented above concerning fire exposed steel structures, it is evident that variations in the structural design considerably can influence the fictitious time of fire duation T_f. For a fire development with an opening factor $A\sqrt{h}/A_t = 0.04\ m^{1/2}$, the diagrams in Figs. 17 to 24 give a variation of T_f which covers the range 0.3 to 0.8 h for the fire load q = 15 and the range 0.45 to 0.95 h for the fire load q = 30 $Mcal/m^2$ of the surface bounding the compartment. To such a statement it must be added that the structural parameters, applied in this comparison, in reality can have a range of variation which is not inconsiderably larger than the range illustrated in Figs. 17 to 24 - cf. in this respect Figs. 8 to 10. With a decreasing value of the opening factor the corresponding variation of T_f increases. An increasing value of the opening factor seems to give the inverse effect.

The results reported in Figs. 25 and 26 for a fire exposed reinforced concrete beam confirm this general statement by showing the obvious influence on T_f of variations in the distance t from the layer of reinforcement to the underneath side of the beam, especially at a fire development with a small value of the opening factor $A\sqrt{h}/A_t$ of the compartment.

From the discussion, now carried through, it follows that a practical application of a differentiated structural fire engineering design, based on the concept of a fictitious time of fire duration T_f, requires the use of design diagrams in about the same extent as a design procedure, directly based on differentiated gastemperature-time curves of the compartment. For both types of design methods such design diagrams have to be drawn up by a combined theoretical and experimental work with an extensiveness which is approximately equivalent for the two types. An advantage of the first-mentioned type of design methods is a better adaptation for a direct use of data from standard fire resistance tests. In favour of the last-mentioned type of design methods speaks a higher degree of suitability for taking into account such influences as varying thermal properties of the structures bounding the fire compartment, temperature-time dependent basic characteristics of the structural materials and of the details of the structure - for instance, effect of disintegration of the materials, enlarged short-time effect of creep and shrinkage, effect of crack formation and spalling, strength of fastening devices for different types of insulation, rate of increase in the depth of the charred layer at timber structures - and the detailed functional behaviour of the structure with regard to different types of fracture and varying load level and degree of restraint. The design methods, directly based on differentiated gastemperature-time curves of the compartment, also are better in agreement with the present development of the building codes and regulations in the direction towards functionally more well-founded requirements.

Finally, it is important to emphasize the fact that the analysis presented above concerning the possibilities of predicting the fire behaviour of structures on the basis of data from standard fire resistance tests mainly has been limited to the influence of varying characteristics of the fire load and the fire compartment. It is also essential to note that the analysis has been based on the present standard fire resistance test procedure which from a functional point of view really can be called in question. For instance, a fundamental improvement of the existing fire test procedure would be to replace the stipulation concerning a fixed temperature-time curve by a requirement which specifies fixed realistic time curves representing the combustion energy supplied per unit time to the fire testing furnace [9], [11], [18].

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