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BEHAVIOUR AND ANALYTICAL DESIGN OF FIRE EXPOSED STEEL STRUCTURES, INSULATED WITH GYPSUM PLASTER SLABS LUND INSTITUTE OF TECHNOLOGY · LUND · SWEDEN · 1978 DIVISION OF STRUCTURAL MECHANICS AND CONCRETE CONSTRUCTION · BULLETIN 64

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BEHAVIOUR AND ANALYTICAL DESIGN OF FIRE EXPOSED STEEL STRUCTURES, INSULATED WITH GYPSUM PLASTER SLABS

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BEHAVIOUR AND ANALYTICAL DESIGN OF FIRE EXPOSED STEEL STRUCTURES, INSULATED WITH GYPSUM PLASTER SLABS

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A development of analytical design procedures, based on well-defined functional requirements, is an important task of the future fire research within different fields of the overall fire safety concept. Such procedures, successively replacing the present, internationally prevalent, schematic design methods, are necessary for getting an improved economy and for enabling more qualified and reliable 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.

In the ideal case, a rational fire design methodology includes as essential components [1]

- * analytical modelling of relevant processes; verification of model validation and accuracy; determination of critical design parameters,
- * formulation of functional requirements, independent of choice of design process and expressed either in deterministic or probabilistic terms,
- * determination of design parameter values, and
- * verification by the means of a reliability analysis that the choice of safety factors leads to safety levels, which are consistent with the expressed functional requirements.

For a fire engineering design of load-bearing structures and partitions, a differentiated analytical procedure is permitted to be applied in Sweden, as one alternative, since about ten years. The procedure constitutes a direct design method based on temperature characteristics of the fully developed compartment fire as a function of the fire load density, the

ventilation of the fire compartment and the thermal properties of the structures enclosing the fire compartment. The design method is approved for a general practical use by the National Swedish Board of Physical Planning and Building [2]. For facilitating the practical application, design diagrams and tables are systematically produced, giving directly, on one hand, the design temperature state of the fire exposed structure, on the other, a transfer of this information to the corresponding design load-bearing capacity of the structure; c.f., for instance [3], [4], [5], [6].

1. Principles of an Analytical Design of Fire Exposed Structures

In a generalized summary way, an analytical design method for fire exposed structures, based on well-defined functional requirements, can be described according to Fig. 1.

The design fire load density, the fire compartment characteristics and the fire extinguishment and fire fighting characteristics constitute the basis for a determination of the design fire exposure, given as the gastemperature-time curve T-t of the fully developed compartment fire. Depending on the type of practical application, the load-bearing function of the structure can be required to be fulfilled for

- * the complete fire process,
- * a shortened fire process, limited by the time $t_{\rm ext}$, necessary for the fire to be extinguished under the most severe conditions, or
- * a shortened fire process, limited by the design evacuation time $t_{\mbox{esc}}$ for the building.

Together with the structural design data, the design thermal properties and the design mechanical strength of the structural materials, the design fire exposure gives the design temperature state and the design load-carrying capacity $R_{\mbox{\scriptsize d}}$ as the lowest value during the relevant fire process.

A direct comparison between the design load-carrying capacity $R_{\rm d}$ and the design load effect at fire $S_{\rm d}$ decides whether the structure can fulfil its required function or not at the fire exposure.

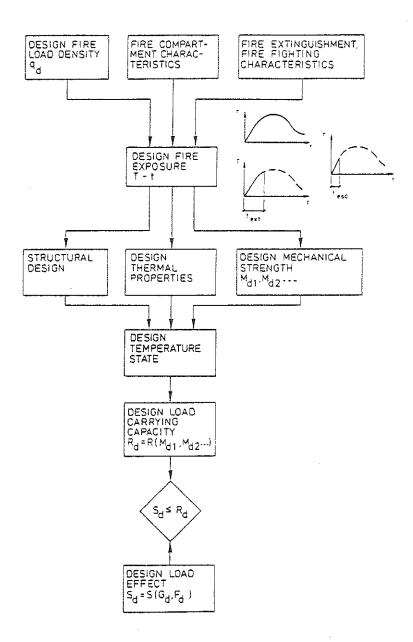


Figure 1. Procedure of an analytical design of fire exposed load-bearing structures

Following a recent draft of safety regulations [7], the determination of the design load effect \mathbf{S}_d starts from characteristic values of permanent and variable loads \mathbf{G}_k and \mathbf{F}_k , connected to a defined probability of excess during a specified time period (Fig. 2). A multiplication by partial factors γ and load combination factors ψ transfers the characteristic load values to design loads \mathbf{G}_d and \mathbf{F}_d . The load combination factors ψ then may be differentiated with respect to whether a complete evacuation of people can be assumed or not in the event of fire. Finally, the design loads are combined and transformed to the design load effect at fire \mathbf{S}_d .

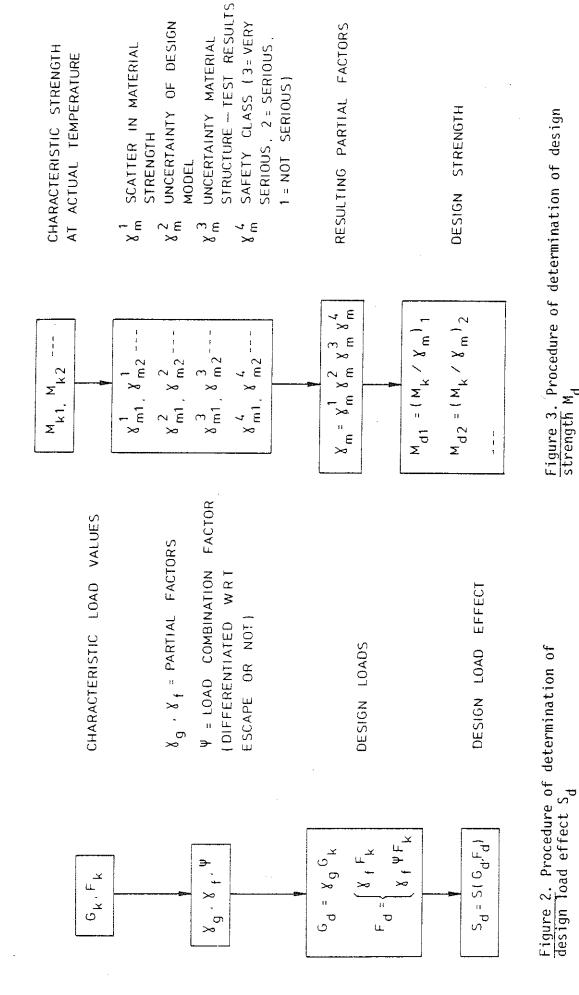


Figure 3. Procedure of determination of design strength $\mathbf{M}_{\mathbf{d}}$

Analogously, the design material strength M_d is to be calculated via characteristic strength values M_k at actual temperature, divided by resulting partial factors γ_m (Fig. 3). The characteristic strength values are defined as corresponding to specified fractiles of the probability density distribution. The different partial factors γ_m^1 , γ_m^2 , γ_m^3 , and γ_m^4 , are expressing the influence of the scatter in material strength, the uncertainty of the design model, the uncertainty in relation between material property in the structure and material property determined in test, and the safety class, respectively. The predicted extent of personal and property damage at failure – very serious, serious, not serious – decides the safety class.

A similar approach – as outlined for the design load effect S_d and the design mechanical strength M_d – can be applied also to the design fire load density q_d and the design thermal properties of the structural materials.

A methodology for a probabilistic analysis of fire exposed steel structures, connected to the described design method, has been developed in [8]. The methodology comprises a general systematized scheme for the identification and evaluation of the various sources and kinds of uncertainty in the differentiated structural fire engineering design. The structure of the methodology is quite general and applicable to a wide class of structures and structural elements.

Described in a more detailed way, a direct, differentiated, analytical design of fire exposed load-bearing structures or structural members, inside a fire compartment, includes the following steps - Fig. 4.

The basis of the design is given by the fully developed compartment fire exposure. Decisive entrance quantities then are

- (1) nominal load and load factor for fire load density,
- (2) combustion properties of this design fire load,
- (3) size and geometry of the fire compartment,
- (4) ventilation characteristics of the fire compartment, and
- (5) thermal properties of structures enclosing the fire compartment.

These quantities jointly determine the rate of burning, the rate of heat release, and the design gas temperature-time curve of the complete fire process. Together with

- (6) structural data for the proposed structure,
- (7) thermal properties of structural materials, and
- (8) coefficients of heat transfer for various surfaces of the structure

this design gas temperature-time curve gives the requisite information for a determination of the transient temperature fields of the fire exposed structure or structural members. With

- (9) mechanical properties of structural materials (Fig. 3), and
- (10) load characteristics

as further entrance quantities the time variation of restraint forces and moments, thermal stresses, and load-carrying capacity R can be determined. The lowest value of R during the complete fire process defines the design load-carrying capacity $R_{\rm d}$.

Over nominal loads and load factors for dead load, live load, etc, statistically representative of a fire occasion, the design load effect at fire S_d is defined, interdependent on non-fire design procedure (Fig. 2).

A direct comparison between the design load-carrying capacity R_d and the design load effect at fire S_d decides whether the structure can fulfilits required function or not at a fire exposure.

For buildings containing activities, which are particularly important from, for instance, an economical point of view, there may be the motive for requiring that the building can be used again after a fire, almost immediately or very soon, for the current activities in a full extent. If a fire engineering design also includes such a requirement on reserviceability of the structure after fire, the design procedure is to be as follows.

From the time curve of the load-carrying capacity R, the design residual load-carrying capacity R_{rd} of the structure after fire is obtained as an end information. This quantity R_{rd} must be compared with the design load effect at service, non-fire state, on the structure S_{rd} , given by the corresponding nominal loads and load factors for dead load, live load, etc.

For fire-exposed, exterior, load-bearing structures, the procedure for a direct, differentiated design will be modified. For such a structure,

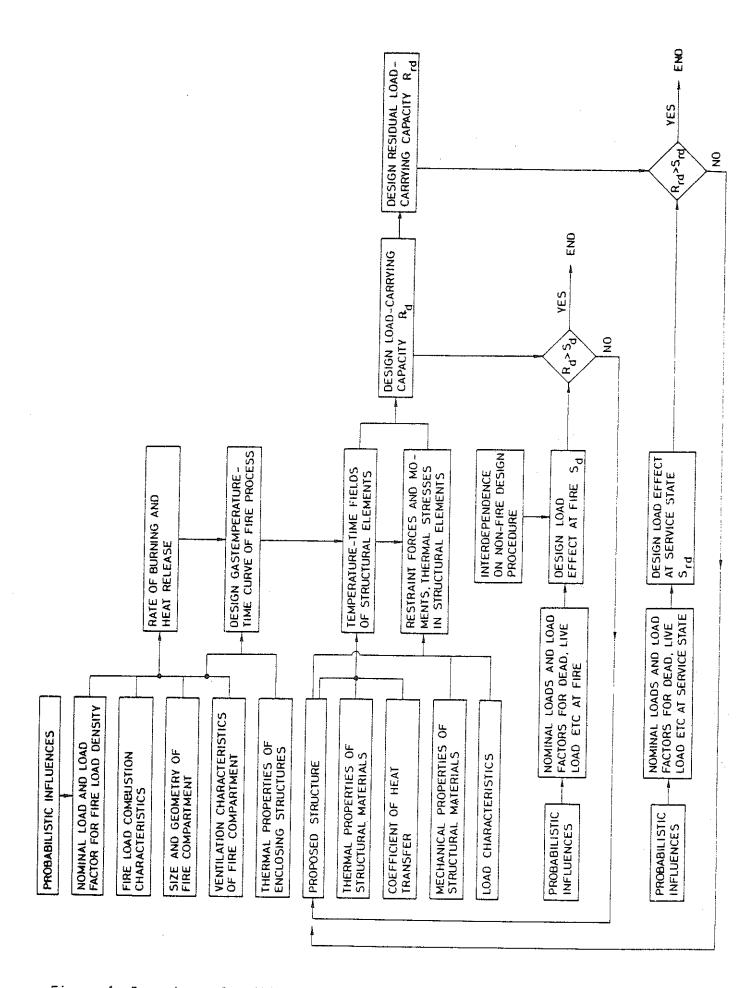


Figure 4. Procedure of a differentiated, analytical fire engineering design of load-bearing structures with additional requirement on re-serviceability after fire. Interior structures

the transient temperature fields are determined by a combined radiation and convection exposure from the flames and combustion gases outside the fire compartment as well as by radiation from the interior of the fire compartment through its window openings; cf., for instance [9], [10].

2. Fire Load Density and Gas Temperature-Time Curves of a Fully Developed Compartment Fire

At known combustion characteristics of the fire load, the gas temperature-time curve of a fully developed compartment fire can be calculated in the individual practical application from the heat and mass balance equations of the fire compartment with regard taken to the size, geometry and ventilation of the compartment, and to the thermal properties of the structures enclosing the compartment - Fig. 5 [2], [4], [6], [11], [12], [13], [14], [15], [16], [17].

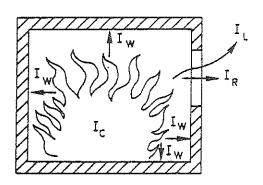


Figure 5. Energy balance equation $I_C = I_L + I_W + I_R$ of a fire compartment. I_C is the heat release per unit time from the combustion of the fuel, and I_L , I_W and I_R the quantities of energy removed per unit time by change of hot gases against cold air, by heat transfer to the surrounding structures, and by radiation through the openings of the compartment, respectively

For interior, load-bearing structures and partitions, the fire engineering design provisionally can be based on gas temperature-time curves T_t -t according to Fig. 6, [2], [4], [6], [13], which applies to a fire compartment with surrounding structures made of a material with a thermal conductivity $\lambda = 0.81 \ \text{W·m}^{-1} \cdot \text{OC}^{-1}$ and a heat capacity $\rho c_p = 1.67 \ \text{MJ·m}^{-3} \cdot \text{OC}^{-1}$ (fire compartment, type A). Entrance parameters of the diagrams are the fire load density q, defined by the formula

$$q = \frac{1}{A_{+}} \sum_{\mu} m_{\nu} H_{\nu}. \qquad (MJ \cdot m^{-2})$$
 (1)

and the ventilation characteristics of the fire compartment, expressed by the opening factor $A \sqrt{h}/A_{\rm t}$ (m $^{1/2}$), where

- A = total area of window and door openings (m^2) ,
- h = mean value of the heights of window and door openings, weighed
 with respect to each individual opening area (m),
- A_t = total interior area of the surfaces bounding the compartment, opening areas included (m^2),
- $m_{ij} = total weight of combustible material <math>v_i(kg)$
- $H_v = \text{effective heat value of combustible material } v \text{ of the fire load } (MJ\cdot kg^{-1}), and$
- $\mu_{_{\rm V}}$ = a fraction between 0 and 1, giving the real degree of combustion for each individual component of the fire load.

As a rule, the design fire load density is to be determined on the basis of statistical investigations for the type of building or premises in question. Such statistical investigations have been carried out for dwellings, offices, administration buildings, schools, stores, and hospitals [2], [4], [6]. As a temporary regulation, the Swedish Building Code authorizes the 80 percent level of the statistical distribution curve to be applied as the design fire load density.

The gas temperature-time curves in Fig. 6 have generally been determined on the assumption of ventilation controlled fires. For fires, which are fuel bed controlled in reality, this assumption leads to a structural fire engineering design on the safe side in practically every case, giving an overestimation of the maximum gastemperature and a simultaneous, partly

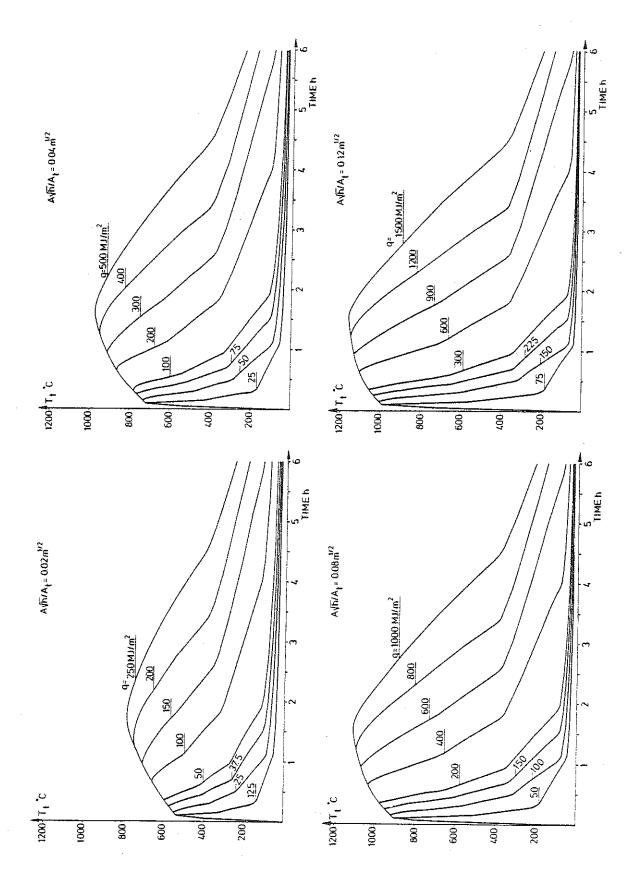


Figure 6. Gas temperature-time curves T_t -t of the complete process of fire development for different values of the fire load density q and the opening factor $A\sqrt{h}/A_t$. Fire compartment, type A

balancing underestimation of the fire duration. For the minimum load-bearing capacity, which thermally can be seen as an integrated effect, the gas temperature-time curves in Fig. 6 give reasonably correct results, verified in [4], [8], [14].

As pointed out, the gas temperature-time curves in Fig. 6 apply to a certain fire compartment, type A, specified with respect to the thermal properties of its surrounding structures. Fire compartments with surrounding structures of deviating thermal properties can be transferred to fire compartment, type A, via fictitious values of the fire load density q_f and the opening factor $(A\sqrt{h}/A_t)_f$ in accordance to Table 1 in the appendix [2], [4], [6].

3. Design Temperature State of Fire Exposed Steel Structures and Partitions

For a fire exposed, uninsulated steel structure, the energy balance equation gives the following formula for a determination of the steel temperature-time curve T_c -t - Fig. 7

$$\Delta T_{s} = \frac{\alpha}{\rho_{s} c_{ps}} \cdot \frac{F_{s}}{V_{s}} (T_{t} - T_{s}) \Delta t \qquad (^{0}C)$$
 (2)

where

 ΔT_s = change of steel temperature ($^{\circ}$ C) during time step $\Delta t(s)$,

 α = coefficient of heat transfer at fire exposed surface of structure $(W \cdot m^{-2} \cdot {}^{\circ}C^{-1})$,

 ρ_s = density of steel material (7850 kg·m⁻³),

 $c_{\rm ps}$ = specific heat of steel material (J·kg⁻¹· 0 C⁻¹),

 F_s' = fire exposed surface of steel structure per unit length (m),

 $V_s = \text{volume of steel structure per unit length } (m^2),$

 $T_t = gas temperature (^{O}C)$ within fire compartment at time t (s).

Eq. (2) presupposes that the steel temperature $T_{\rm S}$ is uniformly distributed over the cross section of the structure at any time t.

The coefficient of heat transfer α can be calculated from the approximate formula

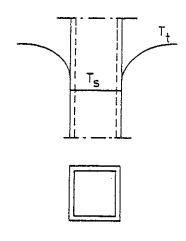


Figure 7. Fire exposed, uninsulated steel structure. T_t = gas temperature within fire compartment, T_s = steel temperature at time t

$$\alpha = 23 + \frac{5.77 \epsilon_{r}}{T_{t} - T_{s}} \left[\left(\frac{T_{t} + 273}{100} \right)^{4} - \left(\frac{T_{s} + 273}{100} \right)^{4} \right] \quad (W \cdot m^{-2} \cdot {}^{0}C^{-1}) \quad (3)$$

giving an accuracy which is sufficient for ordinary practical purposes. ε_r is the resultant emissivity which for practical applications can be chosen according to the following table, giving values which generally are on the safe side.

1. Column, fire exposed on all sides	$\epsilon_r = 0.7$
2. Column, outside a facade	0.3
3. Floor structure, composed of steel beams with a	
concrete slab on the lower flange of the beams	0.5
4. Steel beams with a floor slab on the upper flange	
of the beams	
4a. Beams of I cross section with width/height ≥ 0.5	0.5
4b. Beams of I cross section with width/height < 0.5	0.7
4c. Beams of box cross section and trusses	0.7

In [2], [4], [5], [6], more accurate values are given for the resultant emissivity ε_r , as concerns the application case 4.

At a given gas temperature-time curve T_t -t of the fire compartment, the steel temperature T_s can be directly calculated from Eqs. (2) and (3) with regard taken to the temperature dependence of c_{ps} and α . Such computations have been carried out in a systematized way, giving the basis of design in Table 2 [4]. From this table, the maximum steel temperature $T_{s,max}$ during a complete compartment fire can be determined directly as a function of the fictitious fire load density q_f , the fictitious opening

factor $(A/\bar{h}/A_t)_f$, the F_s/V_s ratio and the resultant emissivity ϵ_r . The values of the table are connected to gas temperature characteristics according to Fig. 6.

For a fire exposed, <u>insulated steel structure</u>, analogously, a simplified energy balance equation gives the following formula for a direct determination of the steel temperature-time curve T_{ς} -t - Fig. 8

$$\Delta T_{s} = \frac{A_{i}}{(1/\alpha + d_{i}/\lambda_{i})\rho_{s}c_{ps}V_{s}} (T_{t} - T_{s})\Delta t \qquad (^{o}C)$$
 (4)

with the additional quantities

 A_i = interior jacket surface area of insulation per unit length (m),

d_i = thickness of insulation (m),

 λ_1 = thermal conductivity of insulating material (W·m⁻¹ °C⁻¹).

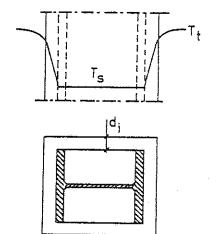


Figure 8. Fire exposed, insulated steel structure. T_t = gas temperature within fire compartment, T_s = steel temperature at time t

Eq. (4) presupposes that the steel temperature T_s is uniformly distributed over the cross section of the structure at any time t, that the temperature gradient is linear and the heating contribution negligible for the insulation, and that the heat transfer is one-dimensional.

Computations, originating from Eqs. (3) and (4), enable a production of a systematized design basis, facilitating an analytical, differentiated fire engineering design in practice. An example from such a design basis is referred in Table 3 [4], giving the maximum steel temperature T s, max during a complete compartment fire for varying values of the fictitious fire load density $\mathbf{q_f}$, the fictitious opening factor $(A\sqrt{h}/A_t)_f$, the structural parameter $\mathbf{A_i}/\mathbf{V_s}$, and the insulation parameter $\mathbf{d_i}/\lambda_i$. The values of the table are connected to gas temperature characteristics according to Fig. 6.

Table 3 has been computed on the assumption of a constant thermal conductivity of the insulating material λ_i , chosen as an average value for the whole compartment fire process. Calculations, carried through systematically, are verifying that this average value of λ_i approximately coincides with the value, determined for an insulation temperature equal to the maximum steel temperature $T_{s,max}$.

For a specific insulating material, systematized design diagrams or tables can be computed very accurately with regard to the temperature dependence of the thermal properties of the steel as well as the insulating material. The influence of an initial moisture content and of a disintegration of the insulating material can be considered, too. Practically, such a determination can be carried out over a numerical data processing by computers on the basis of a finite difference or a finite element method. A great number of design tables, computed according to such an accurate procedure, are presented in [4]. Table 4 exemplifies this, giving the maximum steel temperature $T_{\mbox{\scriptsize s,max}}$ at varying fire and structural design characteristics for a fire exposed steel structure, insulated with gypsum plaster slabs, type Gyproc, of density 790 kg·m⁻³. The thermal properties of the gypsum plaster slabs then have been assumed to depend on the insulation temperature according to Fig. 9 [18], constructed on the basis of results from small scale and full scale tests and of information in the literature [19]. The influence of the disintegration of the slab material is considered.

In [4], an analytical model is derived for a simplified determination of the temperature-time fields of a steel beam construction according to Fig. 10 - composed of a reinforced concrete slab, load-bearing steel beams, and an insulating ceiling - exposed to a fire from below. By applying this computational model in a systematic way, a design basis has been determined, facilitating a calculation of the steel beam temperature $T_{\rm S}$, assumed as uniformly distributed over the cross section of the beams. The design basis is exemplified in Table 5 [4], which gives the maximum steel varying beam temperature $T_{\rm S,max}$ during a complete compartment fire for values of the fictitious fire load density $q_{\rm f}$, the fictitious opening factor $(A\sqrt{\hbar}/A_{\rm t})_{\rm f}$, the structural parameter $F_{\rm S}/V_{\rm S}$, and the insulation parameter $d_{\rm i}/\lambda_{\rm i}$. $F_{\rm S}$ denotes the surface area of the steel beam, less the part covered by the concrete slab, and $V_{\rm s}$ the volume of the steel beam, per unit length. The

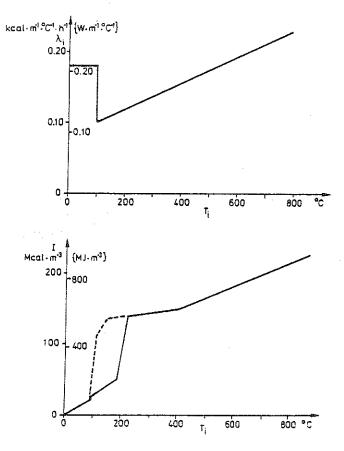


Figure 9. Thermal conductivity λ_i and enthalpy I (= $\{c_pdT\}$) as a function of insulation temperature T_i for gypsum plaster slabs, type Gyproc, of density 790 kg·m⁻³. For enthalpy I, full line refers to a rapid heating and dashed line to a slow heating [18]

values, given in brackets in the table, denote the corresponding maximum temperature at the centre level of the ceiling. The values of the table are connected to gas temperature characteristics according to Fig. 6.

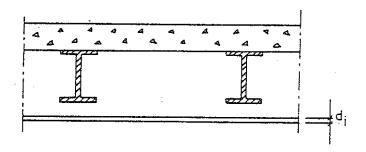


Figure 10. Floor structure, composed of a reinforced concrete slab, load-bearing steel beams, and an insulating ceiling

For several types of steel beam constructions with a suspended, insulating ceiling, the fire resistance of the ceiling and its fastening devices will be the decisive design criterion instead of the temperature of the steel beams. The ceiling can get a serious crack formation or fall down, partially or completely, after a comparatively short fire exposure. Under such conditions, the maximum steel beam temperature cannot be determined from Table 5 solely on the basis of the thickness $\mathbf{d_i}$ and the thermal conductivity λ_i of the ceiling. If results are available for a type of a suspended ceiling from a standard fire resistance test, these results can be used for deriving a fictitious value of the insulation parameter $\mathbf{d_i}/\lambda_i - (\mathbf{d_i}/\lambda_i)_{\text{fict}}$ which describes the real fire behaviour of the suspended ceiling, including its fastening devices. From the test results, also a possible critical failure temperature of the suspended ceiling can be estimated. Cf., further [4].

After the determination of $(d_i/\lambda_i)_{\rm fict}$ and the critical temperature of a type of a suspended ceiling, the analytical differentiated fire design can be carried out by a direct application of Table 5. Parallelly, then the maximum temperature at the centre level of the ceiling according to the table must be controlled against the critical temperature of the ceiling.

Fictitious d_i/λ_i values and critical temperatures have been determined for a number of types of suspended ceilings in a series of standard fire resistance tests performed at the National Swedish Institute for Testing and Metrology in Stockholm [20]. The compositions of these suspended ceilings, the results obtained and the characteristics derived are set out in Table 6 [4].

The design basis, reproduced in Table 2 to 5, generally assumes the steel temperature to be uniformly distributed over the cross section of the beam or column at any time t. A more accurate theory, which enables a determination of the temperature variation over the cross section of the steel structure, is presented in [21], together with computer routines. The algorithm described can easily be coupled to most finite element programs. An illustration of the capability of the theory is given in Fig. 11, which shows calculated temperature distribution along the line of symmetry of a gypsum insulated steel beam with a concrete slab at the top flange at selected times of a standard fire resistance test according to ISO 834.

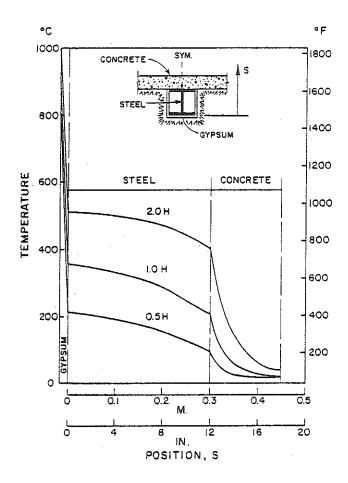


Figure 11. Calculated temperature distribution along line of symmetry of a steel beam, insulated by a 16 mm gypsum board (density 770 kg·m $^{-3}$) and carrying a 150 mm concrete slab on top flange, at selected times of a thermal exposure according to ISO 834 [21]

As a complement to the design temperature state of fire exposed load-bearing steel structures, dealt with above, also some remarks will be given on the fire engineering design of <u>partitions</u>. The performance requirements for partitions imply that these must prevent a penetration of flames and hot gases and limit the rise in temperature on the unexposed side of the construction during a complete compartment fire.

An analytical method for a determination of the temperature-time field in a multi-layer partition is presented in [18]; cf. also [4]. The method considers the temperature dependence of the thermal material properties, an initial moisture content, and a possible material disintegration at specified temperature criteria. An illustrating application of the method is shown in Fig. 12 [18], which gives a summary conception

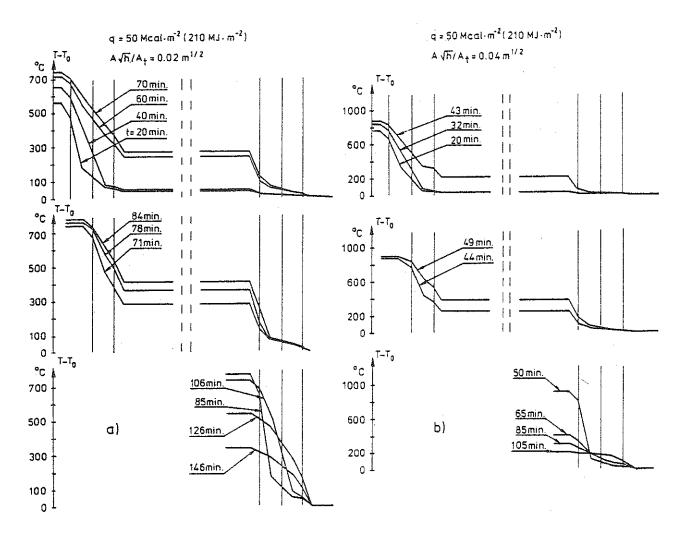
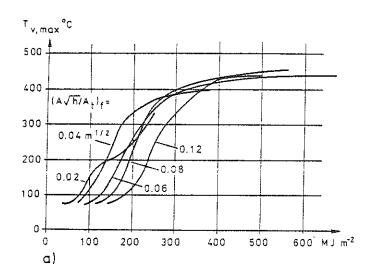


Figure 12. Calculated temperature-time fields for a steel stud wall, insulated on each side with two 13 mm gypsum plaster sheets, type Gyproc, of density 790 kg·m⁻³. The wall is fire exposed on one side with compartment fire characteristics according to Fig. 6: a) q = 50 Mcal·m⁻² (210 MJ·m⁻²), A \sqrt{h} /At = 0.02 ml/2; b) q = 50 Mcal·m⁻² (210 MJ·m⁻²), A \sqrt{h} /At = 0.04 ml/2. T₀ = temperature at time t = 0 [18]

of the fire behaviour of a steel stud wall, insulated on each side with two 13 mm gypsum plaster sheets, type Gyproc, of density 790 kg·m $^{-3}$, fire exposed on one side and acting as a partition. The behaviour has been determined on the basis of temperature dependent thermal properties of gypsum plaster material according to Fig. 9 and a critical failure temperature for a gypsum plaster sheet of 550° C on that side of the sheet facing away from the fire. The results of full scale fire tests confirm this failure criterion.

Fig. 12a describes the fire behaviour of the wall, when it is fire exposed on one side by a compartment fire with gas temperature-time

characteristics according to Fig. 6 - fire load density q = 50 Mcal·m⁻² (210 MJ·m⁻²), opening factor $A\sqrt{h}/A_t = 0.02 \, \text{m}^{1/2}$. The figure gives a calculated failure of the directly fire exposed gypsum plaster sheet after about 70 min and of the next gypsum plaster sheet after about 85 min. The maximum temperature rise on the unexposed side of the wall amounts to 180°C during the complete fire process, i.e. precisely the maximum permissible value according to [2]. Fig. 12b analogously describes the fire behaviour of the wall, when it is exposed to a more rapid compartment fire - opening factor $A\sqrt{h}/A_t = 0.04 \, \text{m}^{1/2}$ - at the same fire load density q. The increase of the opening factor results in a considerably decreased value of the maximum temperature rise on the unexposed side of the wall, which amounts to only about 55°C in this case.



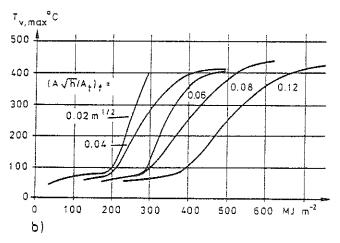


Figure 13. Maximum temperature $T_{v,max}$ during a complete fire process according to Fig. 6 on the unexposed side of a steel-gypsum plaster sheeting wall as a function of the fictitious fire load density q_f and the fictitious opening factor $(A\sqrt{h}/A_t)_f$ of the fire compartment. The wall is insulated on each side with one (fig a) or two (fig b) 13 mm gypsum plaster sheets, type Gyproc, of density 790 kg·m⁻³ [4], [6]

Systematic calculations of the type, illustrated by Fig. 12, lead to design diagrams as shown in Fig. 13 [4], [6], giving the maximum temperature $T_{v,max}$ during a complete fire process on the unexposed side of a steel stud-gypsum plaster sheeting wall as a function of the fictitious fire load density q_f and the fictitious opening factor of the fire compartment $(A\sqrt{h}/A_t)_f$. The two diagrams apply to an insulation on each side of the wall with one and two 13 mm gypsum plaster sheets, type Gyproc, of density 790 kg·m⁻³, respectively. The calculated $T_{v,max}$ values are to be compared with the corresponding maximum temperature, permitted in the Swedish Building Code, which implies 200° C as an average temperature and 240° C as a temperature over limited areas of the unexposed side of the partition [2].

4. Design Load-Bearing Capacity of Fire Exposed Steel Structures

By applying the design tables 2 to 5, the maximum steel temperature $T_{s,max}$ can be determined comparatively quickly for an uninsulated or insulated steel structure, exposed to a complete compartment fire with gas temperature-time characteristics according to Fig. 6. The corresponding design load-bearing capacity of the structure then is obtained by design diagrams of the type exemplified in Fig. 14, 15 and 16.

Fig. 14 and 15 [4], [6] give the design load-bearing capacity ($M_{\rm Cr}$, $P_{\rm Cr}$, $q_{\rm Cr}$) of fire exposed beams of constant I cross section at different types of loading and support conditions, as a function of the steel beam temperature $T_{\rm S}$. The design curves in Fig. 14 apply to a slow rate of heating - assumed to be 4 $^{\rm OC\cdot min^{-1}}$, followed by a cooling with a rate of 1.33 $^{\rm OC\cdot min^{-1}}$ - and Fig. 15 gives the correction ΔB of the load-bearing capacity coefficient B due to a more rapid rate of heating. In the formulas for the load-bearing capacity

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\sigma_s = yield stress of steel material at room temperature (MPa),

L = span of beam (m),

W = elastic modulus of beam cross section (m<sup>3</sup>).
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The design curves in Fig. 14 and 15 have been determined on the basis of the deformation curve of the fire exposed beams calculated by an

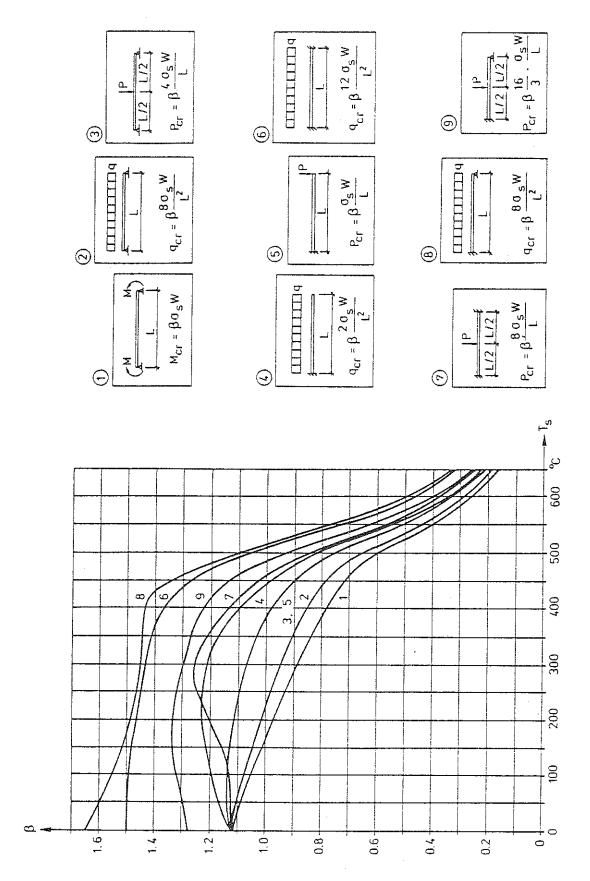


Figure 14. Coefficient ß for determination of critical load (Mcr. Pcr. q_{Cr}) for fire exposed beams of I cross section at different types of loading and support conditions, as a function of the steel beam temperature T_s. The curves have been calculated for a slow rate of heating of 4 °C·min⁻¹ and a subsequent cooling, assumed to be one third of the rate of heating [4], [6]

analytical model, presented in [22], which takes into account the softly rounded shape of the stress-strain curve of steel at elevated temperatures as well as the influence of creep strain. As can be seen from Fig. 15, this influence of creep begins to be noticeable for ordinary structural steels at temperatures in excess of about 450°C. The load-bearing capacity of the beams is defined by the limit deflection criterion according to ROBERTSON and RYAN [23].

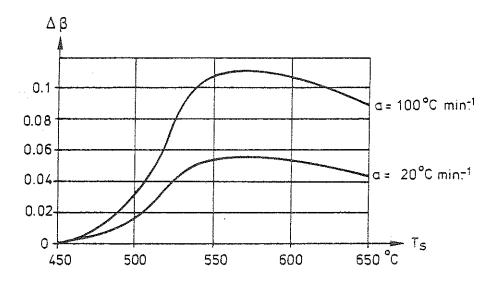


Figure 15. Increase $\Delta\beta$ of coefficient β , determined according to Fig. 14, for a rate of heating a \geq 4 $^{\circ}$ C·min $^{-1}$, as a function of the steel beam temperature T $_{s}$ [4], [6]

The diagrams in Fig. 16 [4] determine the variation with the steel temperature T_S of the relationship between the buckling stress σ_{cr} and the slenderness ratio λ for fire exposed columns, axially loaded in compression. The diagrams apply to steel having a yield stress at room temperature σ_S = 220, 260 and 320 MPa, respectively, and are valid under the presumption that the column is unrestrained with respect to longitudinal expansion during the fire exposure. The σ_{cr} - λ curves have been computed for an initially deflected and excentrically loaded column on the basis of data on the change of the 0.5 % proof stress $\sigma_{0.5}$ and the secant modulus with the temperature, obtained in tension tests at a very slow rate of loading. This implies that a considerable influence of short-time creep at elevated temperatures is included.

For a fire engineering design of columns, partly restrained to a longitudinal expansion, reference is made to [4].

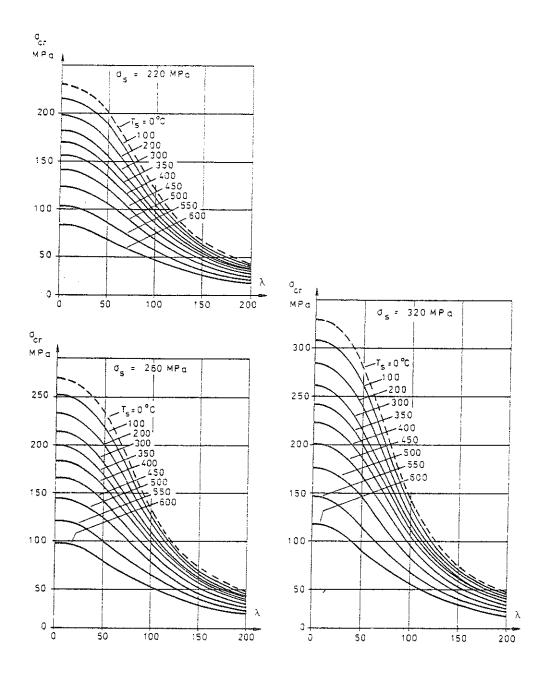


Figure 16. Variation with steel temperature T of the relationship between buckling stress $\sigma_{\text{C}r}$ and slenderness ratio λ for fire exposed steel columns, axially loaded in compression, free to expand longitudinally and made of steel having a yield stress at room temperature $\sigma_{\text{S}}=220$, 260 and 320 MPa, respectively [4], [6]

The design curves, reproduced in Fig. 14, 15 and 16, are generally based on the assumption of a uniformly distributed temperature over the cross section of the steel structure at any time t during the fire exposure. By this assumption, the design curves are directly connected to Tables 2 to 5, determining the design temperature state of the steel structure.

If the analytical, differentiated design of fire exposed steel structures will be further developed in future towards a more accurate determination

of the design temperature state, with regard taken to the temperature variation over the cross section of the steel structure, this will also require a more refined basis of design for the transfer of the design temperature state to the design load-bearing capacity of the fire exposed structure. The first attempts of developing such a more refined design basis now can be noticed in the literature. As a fragmentary example of this development, Fig. 17 [24] shows the calculated variation of the plastic bending moment of a fire exposed steel I cross section as a function of the maximum temperature for various linear temperature distributions over the cross section.

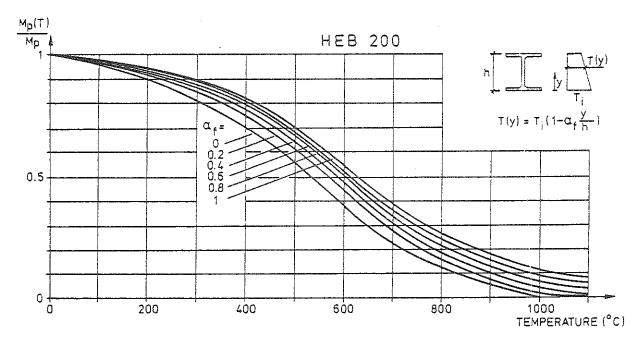


Figure 17. Calculated variation of plastic bending moment $M_p(T)$ in terms of various linear temperature distribution over height of a^p steel I cross section [24]

5. Summary

A differentiated procedure is presented for an analytical fire engineering design of load-bearing steel structures and partitions. The procedure is a direct design method based on gas temperature-time characteristics of a complete compartment fire, which depend on the fire load density, the ventilation of the fire compartment and the thermal properties of the structures enclosing the fire compartment. The practical use of the deisgn procedure has been approved by the National Swedish Board of Physical Planning and Building.

For the practical application of the design procedure, a comprehensive design basis in the form of diagrams and tables has been worked out for a direct determination of the maximum steel temperature during a complete compartment fire and the corresponding design load-bearing capacity of the fire exposed structure. This design basis is exemplified in the paper, focused to steel structures with an insulation of gypsum plaster slabs, primarily for giving a rough impression of the character of the analytical design procedure.

Compared with the conventional fire engineering design, based on classification and results of standard fire resistance tests, the presented analytical design procedure has a more logical structure, based on well-defined functional requirements and performance criteria, gives a structural fire design with a better economy, and leads to a more consistent fire safety level.

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APPENDIX

Table 1. Coefficient K for transforming a real fire load density q and a real opening factor of a fire compartment $A\sqrt{h}/A_t$ to a fictitious fire load density q_f and a fictitious opening factor $(A\sqrt{h}/A_t)_f$ corresponding to a fire compartment, type A

$$q_f = K_f q$$
 $(A\sqrt{h}/A_t)_f = K_f A\sqrt{h}/A_t$

Type of fire		0pen	ing factor	r A√ĥ/A _t	m ^{1/2}	
compartment	0.02	0.04	0.06	0.08	0.10	0.12
Type A	1	1	1	1	1	1
Type B	0.85	0.85	0.85	0.85	0.85	0.85
Type C	3.00	3.00	3.00	3.00	3.00	2.50
Type D	1.35	1.35	1.35	1.50	1.55	1.65
Type E	1.65	1.50	1.35	1.50	1.75	2.00
Type F ¹⁾	1.00-	1.00-	0.80-	0.70-	0.70-	0.70-
·	0.50	0.50	0.50	0.50	0.50	0.50
Type G	1.50	1.45	1.35	1.25	1.15	1.05

¹⁾The lowest value of K_f applies to a fire load density $q > 500 \text{ MJ} \cdot \text{m}^{-2}$, the highest value to a fire load density $q \le 60 \text{ MJ} \cdot \text{m}^{-2}$. For intermediate fire load densities, linear interpolation gives sufficient accuracy.

The different types of fire compartment are defined as follows

Fire compartment, type B: Bounding structures of concrete.

Fire compartment, type C: Bounding structures of lightweight concrete (density ρ = 500 kg·m⁻³).

Fire compartment, type D: 50% of the bounding structures of concrete, and 50% lightweight concrete (density $\rho = 500 \text{ kg} \cdot \text{m}^{-3}$).

Fire compartment, type E: Bounding structures with the following percentage of bounding surface area:

50% lightweight concrete (density $\rho = 500 \text{ kg.m}^{-3}$),

33% concrete.

17% of from the interior to the exterior: plasterboard panel (density $_{\rho}$ = 790 kg·m $^{-3}$), 13 mm in thickness - diabase wool (density $_{\rho}$ = 50 kg·m $^{-3}$), 10 cm in thickness - brickwork (density $_{\rho}$ = 1800 kg·m $^{-3}$), 20 cm in thickness.

Fire compartment, type F: 80% of the bounding structures of sheet steel, and 20% of concrete. The compartment corresponds to a storage space with a sheet steel roof, sheet steel walls, and a concrete floor.

Fire compartment, type G: Bounding structures with the following percentage of bounding surface area:

20% concrete,

80% of from the interior to the exterior: double plasterboard panel (density $\rho=790 \text{ kg}\cdot\text{m}^{-3}$), 2x13 mm in thickness - air space, 10 cm in thickness - double plasterboard panel (density $\rho = 790 \text{ kg} \cdot \text{m}^{-3}$), 2x13 mm in thickness.

For fire compartments, not directly represented in the table, the coefficient K_f can either be determined by a linear interpolation between applicable types of fire compartment in the table or be chosen in such a way as to give results on the safe side. For fire compartments with surrounding structures of both concrete and lightweight concrete, then different values can be obtained of the coefficient $K_{\mathbf{f}}$, depending on the choice between the fire compartment types B, C, and D at the interpolation. This is due to the fact that the relationships, determining K_f , are non-linear. However, the K_f -values of the table are such that a linear interpolation always gives results on the safe side, irrespective of the alternative of interpolation chosen. In order to avoid an unnecessarily large overestimation of $K_{\mathbf{f}}$, that alternative of interpolation is recommended which gives the lowest value of $K_{\mathbf{f}}$.

Table 2. Maximum steel temperature $T_{s,max}$ (°C) for uninsulated steel structure as a function of fictitious fire load density q (Mcal·m⁻²) {MJ·m⁻²}, fictitious opening factor $A\sqrt{h}/A_t$ (m^{1/2}), F_s/V_s ratio (m⁻¹), and resultant emissivity ε_r [4]

[q	AV.	<u>Б</u> <u>Г</u>	т	s.ma	х		AVh	F3	T	s.ma	x		AVħ	F _s	Т ₅ .	.max	-		AVF	F,	T	s,max	
	A,	V3		ε, 0.5	ε _ς 0,7	q	A	$\overline{V_s}$	ε, 0,3	0.5	έ, 0,7	4	At	ν̄.		ε, 0,5	ε _τ 0,7	q	Ar	$\overline{V_s}$	0,3	ε, 0,5	٤,
	0,0	1 125 150 200 400	365 395 410 425 425 425 450	345 385 410 425 425 445 450 380	370 405 425 435 440 445 450		0,01	50 75 100 125 150 200 400	400 435 450 460 470 475 480	420 443 460 470 475 480 485	440 460 470 475 480 485		0,01	25 50 75 100 125 150 200 400	465 4 485 5 495 5 500 5 505 5	23 80 606 605 610 610	445 490 500 505 510 510 515		9, 01	25 50 75 100 125 150 300 400	455 510 525 530 533 533 540	490 525 530 535 535 540 540 540	500 530 535 535 540 540 540
	0,0	75 100	410 445 480 500	445 490 520 540 560, 585	475 520 545 553 573 585		0,02	75 100 125 150 200 400	500 540 565 585 605 625	540 575 600 605 620 630	515 565 595 610 615 625 630	20	0,02	50 75 100	500 5 560 6 595 6 615 6 625 6	30 20 30 40 45	575 620 630 640 645 650	25 [105]	0,02 0,04	50 75 100 125 50 75	555 610 640 650 570 650	000 640 650 655 645 720 420	625 650 653 660 700 760
10 {42}	0,04	75 100 125 130 200 300	350 405 430 495 550 625	400 460 515 355 605 660	450 510 555 595 645 690	15 [63]	0,04	75 100 125 150 50	490 550 600 635 340 425	550 610 655 680 400 490	600 653 690 710 473 573	[84]	0,04	50 75 100 25 30	495 3 585 6 650 1 285 3 440 3	50 50 70 40 40	625 700 740 415 600 700		0,06	50 75 50 75 100 25	525 640 480 590 660 240	600 690 590 700 775	700 790 635 770 -
120	0,06	50 75 100 125 150 200 300	235 305 365 415 450 520 615	275 370 410 450 485 550 680	330 425 435 543 580 660 735		0,06	100 125 150 200 50 75	500 550 590 650 300 380	550 600 630 700 373 465	630 680 720 753 430 535		0,08	100 50 73 100 125 25	390 4 485 5 565 6 630 7 200 2	75 90 90 70 15 33	733 350 670 733 790 305 300		0,12	50 73 100 125 25 30 75	400 500 590 650 505 545 555	460 580 655 720 525 535 560	590 700 500 - 560 560
	0,08	50 75 100	200 270 330 360 410	250 230 400 450 510 390	300 400 460 510 580 660		0,08	100 125 150 200 50 75 100	450 500 555 625 260 340 390	545 595 650 725 290 380 460	605 670 710 783 400 500 600		0,12	75	425 4 400 5 550 6 600 6 430 4	30 60 20 33 00 05	610 700 775 - 430 513	30	0,01	100 125 150 300 400	500 560 560 565 565 600	560 565 565 565 570 640	560 563 563 570 570
	0,12	300 75 100 125 150 200	170 220 240 260 310	700 200 200 310 380 430 500	760 200 350 400 540 620 700			125 130 200 23 50 75 100	450 575 355 430 460 475	540 600 680 343 450 475 480	673 750 - 		Ì	73 100 125 150 200 400	520 5 520 5 525 5 530 3 530 5	15 20 25 25 30 30	520 525 525 530 530 505	[126]	0,02	75 100 75 25 50 75	650 630 710 410 595 705	670 673 703 780 500 680 775	670 975 750 800 580 760
	0,01	300 50 75	450 365 410 430 440 450	620 385 425 445 450 455 460	\$00 405 435 450 460 460 465			125 150 200 400 50 75 100	485 485 485 490 460 530 565	185 490 495 500 515 570 600	490 495 500 500 550 595 615		Ì	75 100 125 150 200 50	590 G 615 G 630 G 645 G 650 G 525 G	20 35 45 50	635 630 650 655 665 660 735		0,08	50 73 25 50 75 100	565 660 290 460 590 665 425	540 665 775 540 660 740	745 - 440 650 770 -
*	0,02	30 75 100 125 150	465 380 455 500 325 550	470 435 500 540 535 570	470 470 535 560 575 380		0,02	125 150 200 400 50 75	505 610 625 635 450 545	610 620 635 643 515 600	630 635 645 645 575 655	22, 5 [94,5]	0,06	25 50 75 100	586 7 320 3 480 5 585 6 633 7 430 5	40 80 50 30 23	760 460 645 740 735 605	(190)	0,30	50 25 50 75 100 125	210 360 430 335 395	760 270 440 555 650 735	325 520 640 730 790
	0,04	75 100 125	600 (340 - 415 4 485 3 525 6	100 185 550 500	600 605 450 540 600 640 665		0,06	100 125 25 50 75 100	600 650 255 390 490 565 620	300 455 555 620 670	705 740 370 530 633 710 750		0,12		610 7 215 2 360 4 465 5 340 6	12 40	725 780 350 540 650 750	90 {380}	0,30		425 650 790	545 790 -	890
12,5 {52,5}	0,06	200 50 75 100 125 150	630 6 290 3 365 4 423 4 480 5 520 5	663 125 126 180 125 160	700 400 495 560 610 630	17,5 [73,5]	0,08	50 75 100 125 150	343 440 500 563 615	435- 530 605 650 705	490 600 670 740 765				650 7								
	0,08	300 75 100 125 150 200	670 7 250 3 325 4 385 4 433 5 485 5 550 6	40 13 .00 75 30 85	705 770 360 455 535 600 650 730		0,12	75 100 123 150	275 350 425 475 525 600	300 430 505 575 645 725	450 530 630 725 773												
	0,12	50 75 100 125 150	200 2 240 3 250 4 340 4 380 5	50 20 00 50	330 410 510 620 690 760																		

Table 3. Maximum steel temperature T ($^{\circ}$ C) for insulated steel structure as a function of fictitious fire load density q (Mcal·m⁻²) {MJ·m⁻²}, fictitious opening factor A/h/At (ml/2), structural parameter A_i/V_s (m⁻¹), and insulation parameter d_i/ λ_i (m^{2.o}C·h·kcal-l)^a. d_i denotes insulation thickness (m) [4]

	AVE	; A	l _j		's,	max.	ı.			AV		,	T _{s.r}	nax		g	4	Vħ	$\frac{A_{i}}{V_{s}}$		Ts,rr	ıax		+ 4	AVh	A		[⊤] s	max	
	AVI	- -			d _i /λ 0,10			d;/λ; 0,30		7 7	,		, <i>d; λ;</i> 5 0.10			,	7	A,	V _s			d;/λ; 0,20			At	V,			d _i â 0,20	
	0,01	10 12 15 20 30 40 10 12 15	5 0 0 0 0 5	38 0 405 420 440 460 470 390 420 450	325 350 365 395 430 445 340 340	28 30 33 37 10 22 25	0 5 5 5 0	215 240 260 290 335 370 180 205 225		0,0	3 7 10 1 12 15 20 40 50	5 470 1 495 5 505 5 513 0 525 0 535 0 395	410 445 463 480	275 330 370 395 420 450 505 225 280	275 320 350 375 410		0	, 02	25 50 75 100 125 150 200 300 400	360 490 550 595 625 645 665 690 700	260 380 445 490 535 555 600 640 670	185 270 340 385 425 460 510 580 610	145 225 280 325 360 395 445 515 560		0,02	25 50 75 100 125 150 200 300 400	445 570 640 670 695 710 725 740 745	330 460 540 580 620 650 680 710 730	230 340 415 470 510 550 600 655 680	180 275 340 395 440 475 530 600
5 3}	0,02	300 400 125 150	5	500 550 575 373 400 450 550 500	400 460 505 270 300 350 420 475 250	31 37 41 19 21 25 31 36 17	0 5 0 0 0	260 320 355 156 175 205 255 300 140	25 {105		100 125 2 150 200 300 400 75 100 125	500 540 560 595 635 650	405 445 470 515 570 605 295 350 330	310 350 375 420 490 525 200 240 270	260 300 320 360 435 470 160 195 220	35		04	25 50 75 100 125 150 200 300 400	275 410 500 560 610 650 700 760	200 300 380 440 480 525 590 665 710	130 205 265 310 350 385 445 530	100 160 210 250 280 310 370 450 510		0,04	25 50 75 100	330 480 565 630 680 715 765	245 350 440 500 550 590 630 725 770	160 250 315 370 410 450 510 600 633	125 195 250 300 340 370 430 510
	0,06 0,08 0,12	200 400 200 300 400 300		100 180 140 150 125 100	295 370 420 255 335 390 250	210 260 305 185 225 270 175) 5 5	170 210 245 145 180 200		0,04	150 200 300 400 75 100 125	550 600 680 725 350 410 455	420 480 535 615 243 295 330	300 350 425 485 170 200 230	250 290 365 420 130 160 185	-	0,	06	50 75 100 125 150 200	555 595 660	250 320 370 415 455 520	165 215 253 295 320 380	125 170 200 235 260 305	45	0,06	25 50 75 100 125 150 200	l	195 300 380 440 490 530 600	125 200 260 310 350 390 450	95 155 205 245 230 310 370
	0,01	400 75 100 125 150 200 300 400	4 4 4 4 5	75 90 00	355 355 415 430 455 480 490	290 280 315 340 365 395 440 460		165 235 270 290 329 355 400		0,00	150 200 300 400 100 125 150 200	500 565 655 710 350 400 450 500	370 430 520 380 255 290 325 380	255 310 380 440 173 195 220 260	205 245 305 360 140 153 175 210		0,0	1 1 1 28 1 2 3	75 100 25 25 50	800 380 450 500 540 715	675 275 325 365 405 470	530 185 220 255 280 340	145 175 200 225 265 345	{190}	0,08	300 400 50 75 100 125 130	373 465 530 590 640	700 765 260 335 395 445 490	540 610 175 225 270 305 340	455 520 135 180 210 240 275
,		200 300 400	4) 5) 5) 5) 6)	00 50 30 L0 50 95	315 355 390 415 470 530 560	240 270 300 325 370 435 475	1 2 2 2 3 3	190 220 250 275 110 170		0,12	300 400 130 200 300 400	600 675 360 430 510 570	470 540 245 300 370 430 310	340 390 175 210 260 300	265 315 140 163 210 240 180	-	0,1	2 1 2 1 2 3 3	00 25 50 3 00 6	175 2 120 2 165 3 145 4 145 4	263 290 325 390 380 345	170 1 195 1 225 1 265 2 335 2	.35 .55 .80 .10 .75 .15		0,12	300 400 75 100 125 150	370 : 445 : 510 :	725 260 315 350 395	235 275	315 400 475 120 155 185 220 260
C	0,04	200 300 400 100	48 54 52 67	0		210 240 260 310 380 440	1 2 2 3 3	50 10 50 10 35		0,01	50 75 100 125 150 200 400		460 490 510 525 535	320 380 420 450 470 500	270 315 365 400 425 460 520		0.0	1	75 5 00 6 25 6 50 6	95 4 35 5 65 5 80 6	95 3 45 4 30 4 10 5 45 5	80 3 35 3 80 4 10 4 60 4	50 15 60 00 35 90		0,30	300 100 150 100	735 5 790 6 325 2 385 2 475 3	560 535 215 265 340	405 470 140 170 225	325 385 115 135 175 210
0),06	125 150 200 300 400 L25 L50	39 43 49 58 64 34 37	0 : 0 : 0 : 0 :	120 170 150 105 140	200 220 260 325 380 165 185	11 21 20 31	55 75 10 60 10 25	30	0,02	25 50 75 100 128 150 200	140 510 550 580 605	345 405 450 490 520	163 250 305 350 385 420 470	130 200 250 290. 325 355 400		0,04	10 12 15	0 7: 5 3: 0 4: 5 5: 5 5: 5 6-	5 7 30 2: 15 3: 25 4: 35 4: 5 5:	00 8 20 1 30 2 30 2 55 34	50 60 45 11 25 18 90 23 40 23	15 10 15 10					- Pin		
-	,12 3	200 300 100 200 300	44 53 60 36 42 46	0 4 0 4 0 2	00 50 50 05	225 280 340 180 215 250	17 21 26 14 17 20	15 30 10 75	LD6	0,04	300 400 50 75	665 675 370 450 510 360	610 640 270 340 400 440	540 570 185 240 280	470 515 140 185 220 250 285	[108]	0.06	204 301 404 50 75	0 75 0 75 0 - 0 38 5 47 0 54	0 61 0 69 74 5 27 5 35 0 40	5 47 5 56 0 63 5 18 0 23 5 28	75 39 15 48 10 54 15 14 15 18 0 22	5 0 5 0 5 5							
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q	AVE			T _{s,r}	nax			AVħ	A		T _{s.m}	ıex	····	q	ΑVħ			T _{s,m}	ax			AVħ	A;		T _{s.m}	ax	
	At	·V,	d;12 0.0	, <i>d;là;</i> 5 0.10	<i>d;(2,</i> 0,20	, <i>d_i λ_i</i> 0,30	9	At	V,		<i>d_i î.;</i> 0,10			-	At	V,		<i>d_ijλ_i</i> 0,10			4	At	v.			¢;/λ; 0,20	
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	0,04	25 50 75 100 125 150 200	350 500 600 655 705 740 785	255 385 460 525 575 615 675	170 270 340 395 435 475 540	135 210 265 315 355 395 450		0,04	25 50 75 100 125 150 200 300	405 560 650 715 755 790	300 430 515 580 640 675 730 795	200 305 380 440 490 530 600 680	130 240 310 360 403 440 505		0,06	50 75 100 125 150 200 300	565 670 740 790 -	415 510 585 640 685 755	285 365 425 480 525 593 695	225 290 345 390 430 500	120	0,06	100 125 150 200 25 50 75	- - - - - - - - - - - - - - - - - - -	750 800 - - 325 490 595	575 635 685 753 220 340 435	475 535 580 653 165 260 340
50 (210)	0,06	150 200	300 445 540 610 665 710 775	750 -795 210 320 400 465 515 560 625	625 690 135 215 275 330 375 410 475	545 600 105 170 220 260 300 330 395	60 (250)	0,06	25 50 75 100 125 150 200 300 400	345 500 600 670 725 765 -	240 380 450 515 570 615 685 775	155 240 315 375 415 460 525 625 695	120 195 250 300 340 375 435 530 600	75 (315)	80,0	150 200 300 400	350 510 613 700 750 800	240 365 455 530 585 640 710	160 250 320 375 425 470 545 650 730	120 190 250 300 340 385 450 550 625	(50e)	0,08	100 125 150 200 25 50 75 100 125 150	390 565 690 760	740 780 250 390 495 565 640	505 560 610 690 165 260 340 400	400 450 500 580 130 210 270 320 370
	0,08	300 400 25 50 75 100 125 150 200	260 400 500 555 615 665 750	725 790 189 275 350 410 460 505 380	570 635 115 180 240 290 325 355 425	480 545 90 140 190 225 255 295 350			125 150 200	68 0 725	200 315 400 460 515 560 640 750	135 210 273 325 365 400 475 580 650	100 160 210 253 290 330 390 480 550		0,12	150 200 300 400 75	525 600 680 725 800	375 410 500 550 620 730 800	190 250 300 350 390 450 550 650	150 200 240 275 300 360 450 530		0, 30	200 300 75 100 125 150 200 300	4.35 51.0 575 625 705	760 760 300 355 410 455 530 640	500 573 700 195 235 270 303 365 463	410 480 590 150 180 210 240 255 370
	0,12	150 200	320 410 480 550 600 875	680 750 220 290 345 390 430 500	260 295 350	430 500 110 145 175 200 235 280		0,12	75 100 125 150 200 300 400	470 550 600 650 735	385 430 480 550 660 730	160 210 250 300 330 400 500 575	125 170 200 235 265 310 400 463			200 300 400 25 50	365 410 465 535 635 715 630 760	250 285 315 385 480 530 480 640 725	165 190 210 255 335 390 330 490 590	130 150 170 200 260 310 260 395 490			(400 i	<u>-</u>	720	540-	435
,	0, 30	150 200 300	780 - 305 350 410 500 575	365	245	350 413 110 125 145 190 225		0,30	150 200 300	395 460 355	265 325 410	215 280	125 148 163 220 260		0,06	100 125 150 25 50 75	- - - 450 625 730 795	770 790 - 313 470 570 640	650 700 730 210 325 410 475	560 610 650 160 255 330 390 435							
												٠		90 {380}	0,08	50 75	570 680 733 -	275 415 510 390 650 700	750 750 180 285 360 420 480 520	480 550 665 140 220 285 340 390 430 500 600							
														,	0,12 1 22 3	25 50 75 .00 25 .50 .00 .00	475 590 370 740 800	220 330 425 495 350 600 680	140 220 285 340 395 440 500	105 175 225 275 305 350 403 505							
															0,301 2	00 25 50 60 00	125 80 330 10	290 1 335 3 375 3 445 3	195 1 225 1 250 1 300 1	125 150 175 195 135 1805							

Table 4. Maximum steel temperature T_s , max ($^{\circ}$ C) for a steel structure insulated with gypsum plaster slabs, type Gyproc (ρ_i = 790 kg·m⁻³), as a function of fictitious fire load density q (Mcal·m⁻²){MJ·m⁻²}, fictitious opening factor $A\sqrt{h}/A_t$ ($m^{1/2}$), structural parameter A_i/V_s (m^{-1}), and insulation thickness d_i (mm) [4]

_	AVA	A,	T _s .	max		AVT	A_i	Ts	max		AVE	A;	тs	.max		AVA	A;	Ts.	max	4	AVT	A; 7,	T _{S.1}	max
q	A	A/Vs	<i>d_i</i> 13	<i>d;</i> 26	4	At	V,	13	<i>d;</i> 26	4	At	\overline{V}_{s}	<i>d</i> ; 13	<i>d</i> ; 26	4	Az	V,	<i>d_j</i> 13	<i>d;</i> 28		A	7,	<i>d;</i> 13	d; 26
15 [63]	0,01	300 400 125 150	315 335 365 395 415 300 325 350	200 215 235 260 275 150 165 200		0,01	25 50 75 100 125 150 200 300	315 415 465 495 510 525 535 550	210 305 360 395 420 440 465 495		0,02	25 50 75 100 125 150 200 300	305 435 525 600 640 675 700 720	195 290 345 390 425 500 583 650		0,0:	25 30 75 100 125 150 50	390 550 635 725 755 763 410 500	250 370 500 570 615 680 275 330		0,04	25 30 75 25 50 75 100 125	395 620 735 315 465 590 775	350 535 650 265 390 475 550 630
	0,04	300 400 300	405 435 300 330 345 380	215 230 120 125 230 260		0,02	50 73 100 125	560 350 410 460 495 520	510 215 265 305 335 365		0,04	50 75 100	350 425 485 535 605 690	200 260 300 325 353 400		0,04	100	575 650 745 - - 350	38 0 42 0 45 3 50 0 63 5	1	0,08	150 73 100 125 150	- 410 525 630 700	675 325 400 480 535 595
	0,01	125 150 200 300 400 75 100	405 420 440 465 480 300 345	280 300 325 355 375 180 200	30 {126	0,04	300 300 400 75 100 125 150	570 640 665 345 400 435 470	400 450 470 185 215 245 260	{res	0,06	300 400 73 100 125 150 200	780 - 365 420 450 485 600	495 560 185 215 235 260 300	50 [210]	0,06	75 100 125 150 200 300 400	435 510 570 600 750	265 310 343 375 425 495 535	[315	0,12	200 75 100 125 150 200	320 400 475 340 650 765	675 230 300 350 375 410 450
20 (84)	0,02	125 150 200 300 400 125 150	375 400 440 490 520 300 325	220 235 265 300 320 130 140		0,06	200 300 400 100 125 150 200	520 630 695 330 365 395 445	300 350 380 140 155 175 200		0,08	300 400 75 100 125 150 200	730 800 305 360 400 445 510	355 385 160 185 200 220 250		0,08	150 200	300 375 440 490 550 650	200 245 250 300 330 375 415		0,30	300 400 150 200 300 400	- 300 325 395 435	563 655 115 115 125 150
	0,04	200 300 400 300 300 400	370 435 475 300 350 400	133 175 200 110 115 120		0,08	300 400 125 150 200 300	550 600 305 245 390 450	235 255 120 125 135 155		0,12	300 400 125 150 200 300	315 315 350 400 450	295 325 115 120 135 145		0,12	300 400 100 125 150 200 300	340 385 420 470 575	500 145 150 153 200 220		0,04	50 25 50 75 100	305 365 530 785 -	310 450 550 720 260
	0,08	300 400 50	295 320 360	100 110 250		0,12	300 400	330 380	170 120 125			400 25 50	350 495	155 225 335		0,30	400 300 400	735 220 260	230 100 105	90	0,08	50 75 100	470 625 500	395 485 550
	0,01	75 100 125 150 200 300 400	410 440 470 480 500 520 530	300 335 360 375 410 440 465		0,02	50 75 100 125 150 200 300 400	390 463 520 560 595 640 690 705	255 305 345 380 420 490 540 570		0,02	75 100 125 130 50 75 100 125	600 685 715 740 380 460 525 585	405 435 500 600 230 290 330 385		0,02	25 50 75 25 50 75 100 125	465 690 770 325 470 575 730	320 450 680 265 390 455 520 595	[380]	0,12	125 50 75 100 125 150 200	375 465 350 650 300	300 375 440 480 525 600
25	0,02	75 100 125 150 200 200 400	355 400 430 455 500 550 585	225 255 285 300 335 375		0,04	50 75 100 125 150 200 300	310 385 445 490 535 600 710	170 230 265 295 315 355 425	45 {190}	0,04	150 200 300 400 50 75	675 775 - - 320 400	400 445 555 650 173 220	60	0,06	150 50 75 100 125 150	400 490 610 710	295 375 425 450 490		0,30	300 400 100 125 150 200 300	295 325 360 400 480	115 125 135 140 170
[105]	0,04	100 125 150 200 300 400	335 375 400 455 550 600	225 250 295	35 {147}	0,06	400 75 100 125 150 200	775 320 375 415 410 430	475 150 175 190 215 245		0,06	100 125 150 200 300 400	460 505 540 670 - - 340	253 290 315 360 425 450	(250)	0,08	200 50 73 100 125 150 200	350 435 500 535 650 780	250 315 365 400 440 500		0,04 0,06 0,08	400 25 50 25 50 25 50 25 50	550 690 - 465 760 390 610	200 550 - 410 680 345 510
	0,06	150 200 300 400	330 375 415 500 320	130 135 150 175 195 115		0,08	400 100 125 150 200	640 700 315 355 395 450	290 315 140 150 160 180		0,08	100 125 150 200 300 400	400 445 495 585 685 760	230 250 265 310 350 400		0,12	300 400 75 100 125 150	340 400 450 500	550 660 195 220 250 280	120 {500}	0,12	75 25 50 75 100 125	305 470 665 800	710 255 390 500 600 710
				120		0,12	100 200 300	520 590 340 390 450	220 245 120 130 135		0,12	100 125 150 200 300 400	305 345 375 420 500 615	125 125 130 155 170 175		30	300 400	375 690 - 300 325	320 355 400 105 120		0,30	75 100 125 150 200 300	323 380 435 475 560 745	180 220 250 275 295 350

Table 5. Maximum steel beam temperature T_s , max (O C) for a steel beam construction according to Fig. 10, with an insulation in the form of a suspended ceiling, as a function of fictitious fire load density q (Mcal·m-2){MJ·m-2}, fictitious opening factor $A\sqrt{h}/A_t$ ($m^{1/2}$), structural parameter F_s/V_s (m^{-1}), and insulation parameter d_i/λ_i (m^2 . O C·h·kcal-1)c. The maximum temperature in the suspended ceiling is given in brackets [4]

q	AVh At	F ₃	Maximum steel temperature $T_{s,max}$ and (maximum suspended ceiling temperature (σ_i/λ_i) flot	9	AVh At	$\frac{F_s}{\overline{V}_s}$	Maximum steel temperature $T_{s,max}$ and () maximum suspended ceiling temperature $(G_i \hat{\lambda}_i)_{TICL}$
			0,05 0,10 0,20 0,30	7			0,05 0,10 0,20 0,30
	0,02	50 100 200 300	130 90 65 50 180 130 130 90 (410) 70 230 (470) 170 (440) 115 (410) 90 260 190 130 100		0,02	50 100 200 300	435 315 200 160 450 (615) 340 (570) 240 (530) 185 (500) 455 350 250 200
15	0,04	50 100 200 300	100 70 45 40 150 (565) 100 (530) 65 (500) 70 (475) 200 170 110 80	60	0,04	50 100 200 300	340 225 145 110 400 285 (630) 185 (590) 140 (560) 435 (680) 320 220 (590) 165 (560) 445 330 230 180
{63 }	0.08	50 100 200 300	65 50 35 25 95 70 630) 50 40 (570) 150 675) 100 (630) 65 (590) 50 (570) 190 125 90 60	{2 50}	0.08	50 100 200 300 50	250 160 100 75 340 225 130 160 100 415 (750) 285 (700) 185 (650) 135 (625) 445 315 210 155 190 120 75 60
	0,12	50 100 200 300	40 35 (690) 30 (650) 25 (620) 60 (735) 45 70 50 40 155 100 60 45 200 140 95 75		0, 12	100 200 300	190 120 75 60 660 285 (780) 185 110 680 660 375 250 155 110 420 290 185 130 475 330 205 150
	0,02	50 100 200 300	260 (510) 185 (470) 125 (435) 100 (420) 320 245 170 130	90	0,04	100 200 300	510 (740) 370 (680) 250 (630) 190 (600) 515 (740) 385 270 215
25	0,04	50 100 200 300	160 110 75 55 230 (600) 150 (565) 100 (530) 75 290 205 135 (530) 100 (515) 225 235 155 115	[380]	0,08	50 100 200 300	345 225 130 100 430 290 180 (675) 130 (650) 480 (790) 340 (730) 225 (675) 170 (650) 495 360 250 190
[105]	0,08	50 100 200 300	115 75 50 40 160 (680) 110 (635) 70 (595) 55 (570) 240 (880) 150 - 120 90	120	0,04	50 100 200 300	560 400 260 290 570 420 (715) 300 (660) 230 (630) 575 425 300 230
	0,12	50 100 200 300	80 60 40 30 130 80 60 60 45 190 (740) 125 (690) 80 (650) 60 (620) 235 160 100 75	[50 0]	0,08	50 100 200 300	425 280 160 120 495 345 (750) 210 (895) 195 520 (810) 375 (750) 250 (895) 195 525 385 260 205
	0,02	50 100 200 300	300 220 143 110 360 260 175 135 380 290 250 200 (480) 385 295 210 165		<u> </u>		
40	0,04	50 100 200 300	240 160 105 80 315 (645) 220 (600) 140 (560) 100 (535) 370 290 195 150				
[168]	0,08	30 100 200 300	170 110 70 55 245 (715) 160 (665) 100 (625) 75 220 (665) 140 (625) 105 (600) 380 260 165 120			•	
	0.12	30 100 200 300	130 85 55 45 200 (750) 130 (700) 85 (660) 85 (630) 340 225 145 100		,	{ 0	0,05 m ² °Ch/kcai = 0,043 m ² °C/W 0,10

Table 6. Summary results of standard fire resistance tests on some types of suspended ceilings and connected values, derived from the test results, for $(d_i/\lambda_i)_{\mbox{fict}}$ and critical temperature of the ceilings [4]

			Resistance time in standard fi test		Estimate $(d_i / \lambda_i)_{fi}$		Estimated critical suspended
No	Make	Material	(min)	Remarks	kcal	(m w)	ceiling tempera- ture(°C)
1 2	Gyproc	2x13 mm gypsum plaster stabs no giass fibre reinforcement	30-40	All tests were discontinued because the suspended ceiling fell down. The	0,075	0,064	625
3		1x13 mm gypsum piaster siabs 0.25% g (r 1x16 mm gypsum plaster siabs	48	critical temperature had not been reached in the steel girders	0,075	0.064	650
4		0. 25% g i r 2x13 mm gypsum plaster slabs	49		0,10	0.086	650
5		0. 25% g f r 3x13mm gypsum plaster slabs	60		0,15	0,129	650
6		0.25% g f r 2x20 mm gypsum plaster slabs	75-80		0,25	0,215	625
7		0.25% g f r 2x13 mm gypsum plaster slabs with 13 mm mineral wool	80	•		0,258	625
8		between them 2x13 mm gypsum plaster slabs with 13 mm mineral wool	45	plaster slabs were not reinforced	0,30	0,258	550
9		between them 2x13 mm gypsum plaster sisbs	50		0,30	0, 258	550
.0		with 43 mm straw between them 2x13mm gypsum plaster slabs	47		0,30	0,258	550
		with 43 mm straw between them	54		0.30	0.258	550
.1	ingenjörs- firma Zero	Soundex special suspended ceiling tiles. Cast giass fibre reinforced gypsum plaster tiles with "ridges" in a grid pattern. Tile thickness 18 mm, at the ridges 38 mm	, ,	Parts of the ceiling fell down after 90 minutes. Max, steel temperature approx. 440°C	0, 1-5	0,129	700
12	Consentus	Armstrong 13 mm thick	30	No visible damage to suspended ceiling. Max steel temperature	0, 05	0,043	550
.3		Mineral wool acoustic 16 mm thick	80	about 450 °C	0.075	0,064	>(725) ²
4		Type minaboard 13 mm thick	85		0.075	0,064	>(725) ⁸
3		Deflamit-Asbestolux (9 mm Deflamit + 15 mm mineral wool + 9 mm eternit)	90	No visible damage to suspended ceiling. Max steel temperature about 300 °C	0, 20	0,172	>(67%)4
li		Celotex Acoustiformat 15 mm thick glass fibre slab	90	No visible damage to suspended ceiling. Max steel temperature	0,10	0,086	(725) ^a
17	Rockwool	Rockfon Decor 851 (15 mm thick mineral wool slab)	66	about 450 °C. The test was dis- continued because the suspended ceiling fell down. The critical temperature had not been reached in the steel girders.	0,20	0,172	600

a No damage to the suspended ceiling. Calculated temperature in the suspended ceiling when the test was discontinued.