Characteristics of fire exposure - with particular reference to steel structures

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I. INTRODUCTION

The following presentation specifies the thermal characteristics of the compartment fire exposure and the standard fire exposure as a basis for an analytical fire design of load bearing structures, particularly steel structures. The connection between the two types of exposure is dealt with according to the concept of equivalent time of fire exposure, given in an approximate as well as in a more accurate form.

The document was drafted for and included as Chapter II and Appendix A in the "Design Manual on the European Recommendations for the Fire Safety of Steel Structures", Publication No 35 of the European Convention for Construction Steelwork (ECCS), Brussels 1985. The Design Manual was prepared within ECCS Technical Committee 3 by a drafting group with the following membership: J. Witteveen, chairman; L. Twilt, secretary; S. Bryl; J.P. Favre, J. Kruppa, M. Law and O. Pettersson.

II. FIRE EXPOSURE

Terminology

The following terminology is used to describe different types of fire:

A real fire is a developed fire in a building, influenced or not by an extinction system and/or fire brigade action.

An experimental fire is a test fire with specified characteristics and may be small scale or large scale.

A design fire is a fire with a specific thermal exposure, to be used in a structural design. If the thermal exposure is given by the standard temperature-time curve according to the ISO Standard 834, the design fire is the standard fire. If the thermal exposure simulates a real fire in a fire compartment in a simplified and idealized way, it is a compartment fire. Such a fire can be specified either by the variation with time of the heat flux to an exposed structure or structural member or by the variation with time of the gas temperature in the compartment.

II.1 Introduction

As stated in chapter I, there has been important progress during the last ten years in the development of computation methods for analytical structural fire engineering design. For steel structures, this has reached a stage where an analytical design can be carried out for most practical applications on the basis of either the standard fire or a compartment fire which takes into account the combustion characteristics of the fire load, the ventilation of the fire compartment and the thermal properties of the structures enclosing the fire compartment.

In spite of this development, the standard fire resistance test still predominates internationally as the basis for fire classification and design. That is the main reason why the ECCS-Recommendations are limited, in first place, to an analytical determination of the fire resistance of load bearing steel elements and structural assemblies thermally exposed to the standard fire.

Where analytical structural design for a compartment fire is concerned, this can be carried out either by a direct use of the time variation of this exposure or, more roughly, by applying the concept of equivalent time of fire exposure, which relates the compartment fire to the standard fire. This concept can give an improved classification for fire ranking or grading of structural elements, when integrated with a probabilistic model, and taking into account, [1] - [12]:

* the uncertainties of the numerical values of the influence variables (stochastic variables),

* the uncertainties of the prediction models for the heat exposure and the thermal and structural response,

* the probability of occurrence of a developed fire - depending on the compartmentation, the fire brigade action and an automatic extinction system, if any, and

* the consequences of a structural failure - depending on such factors as the occupancy, the height and volume of the building and the importance of the structure or structural member to the overall stability of the building.

The following presentation opens with an outline description of the main characteristics of the fire load with examples of fire load statistics found in recent investigations. The main part of the chapter then deals with analytical models for the design fire exposure with reference to the compartment fire, the standard fire and the concept of equivalent time of fire exposure. The presentation concentrates on the standard fire and the equivalent time of fire exposure, to match the ECCS-Recommendations.

II.2 Fire Load Density

Ordinarily, the fire load in a compartment is defined as the total quantity of heat Q released on complete combustion of all combustible materials, contained inside the fire compartment, inclusive of furnishings, surface material, linings and coverings on walls, roof and floor as well as the load bearing and non-load bearing structure or structural members. Divided by a characteristic reference area, Q gives the fire load density q. Most countries use the floor area A_f as the reference area, while some countries use the total interior area A_t of the surfaces bounding the fire compartment, including all openings. The alternative use of the bounding area A_t originates from the fact that this quantity is a fundamental parameter in the heat balance of the compartment fire.

The two versions of the fire load density are given by the formulae

$$q_f = \frac{1}{A_f} \Sigma m_\nu H_\nu \qquad \text{(II-1a)}$$

$$q_t = \frac{1}{A_t} \Sigma m_\nu H_\nu \qquad \text{(II-1b)}$$

where

q_f = fire load density, per unit floor area (MJ x m^{-2}),

q_t = fire load density, per unit area of bounding surfaces ($MJ \times m^{-2}$),

m_ν = total mass of combustible material (kg),

H_ν = calorific value of combustible material ($MJ \times kg^{-1}$),

A_f = floor area of the fire compartment (m^2),

A_t = total interior area of the surfaces, bounding the fire compartment, including all openings (m^2).

The calorific values of some solid, liquid and gaseous materials are given in table II.1.

For a fire compartment with a guaranteed permanent use and fittings, the design value of the fire load density can be directly determined according to equation II-1. Such an individual survey is worthwhile doing if the fire load statistics for the relevant type of fire compartment have a large coefficient of variation. The determination may, however, result in certain drawbacks in the event of future alterations and rearrangement in the building. It is therefore more convenient to determine the design fire load density on the basis of statistical investigations for the type of building or premises in question. Such statistical investigations have been carried out in several countries for dwellings, offices, administration buildings, schools, stores, and hospitals - cf., for instance [13] - [19].

Table II.2a gives an example of fire load statistics according to recent Swedish investigations [15], [16]. The reported values are instantaneous values, referred to unit area of the surfaces bounding the fire compartment and determined according to equation II-1b. The table gives the average value, the standard deviation and the characteristic value, defined as the 0.8 fractile value, as authorized in the Swedish Building Code at present [20]. In addition, table II.2b gives the corresponding characteristic value of the fire load density q_f per unit floor area [21] , based on the results of the same statistical survey. Roughly, the values of the fire load density given in tables II.2a and b are on the same level as corresponding values, obtained in German, Swiss [13], [14], [17] and US fire load surveys [18], [19]. This is illustrated in table II.2c [13], which gives the average value and the standard deviation of the fire load density q_f per unit floor area from a very comprehensive investigation carried out by ECCS for various types of fire compartments in office buildings.

As a rule, complete combustion of all combustible materials in a fire compartment does not occur. This can be allowed for by using the following relationships for the fire load density:

$$q_f = \frac{1}{A_f} \Sigma \mu_\nu m_\nu H_\nu \qquad \text{(II-2a)}$$

$$q_t = \frac{1}{A_t} \Sigma \mu_\nu m_\nu H_\nu \qquad \text{(II-2b)}$$

where

μ_ν = a fraction between 0 and 1, giving the real degree of combustion for each individual component of the fire load.

The non-dimensional factor μ_ν varies according to the type of fuel, its geometrical properties and position in the fire compartment, and the fire environment (heat flux and duration of heating). Bookcases, stacks of papers and floor coverings are examples of fire load components whose real degree of combustion is usually low, and whose μ_ν values consequently are well below unity. At present, there is a lack of experimentally verified μ_ν values for a range of fire environments so that, normally, formula II-2 cannot be used. A test apparatus and a test procedure for evaluating μ_ν in one specific environment are described in [1] and [2], which include comprehensive lists of values, determined for various materials, under this condition. A more differentiated procedure for determining μ_ν, which takes into account the porosity of the fire load and the temperature-time curve of the design fire is presented in [13] and [14]. The procedure is iterative and primarily applicable to stacks of papers in cabinets. However, the values of the fire load density reported in tables II.2a-c generally assume $\mu_\nu = 1$.

II.3 Analytical Models of Design Fires

II.3.1 Compartment Fire Exposure

In practice, it is the fully developed regime of the compartment fire which significantly affects the behaviour of the load bearing structure or structural members. The essential influences on this part of the fire process - the post-flashover compartment fire - are

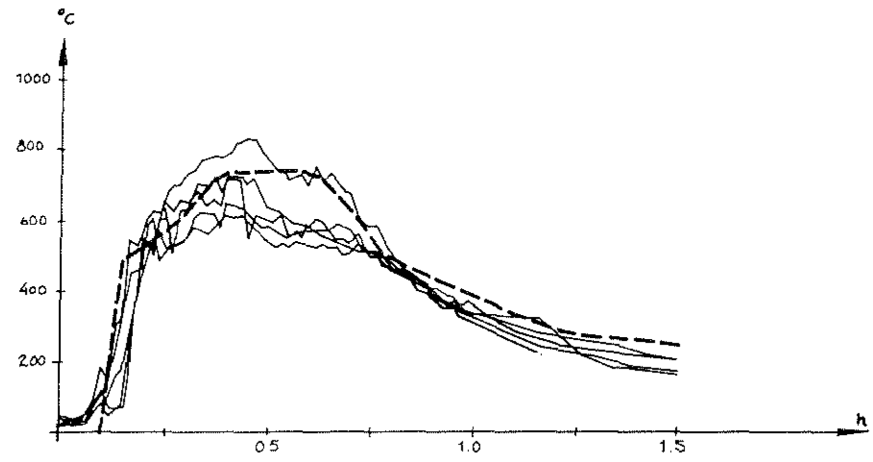
* amount and type of combustible materials in the compartment (fire load),
* porosity and particle shape of the fire load,
* distribution of the fire load in the compartment,
* amount of air per unit time supplied to the compartment,
* geometry and openings of the compartment, and
* thermal properties of the structures, enclosing the compartment.

For given combustion characteristics of the fire load, the variation with time of the heat flux to an exposed structure or structural member or the gas temperature-time curve of the fire compartment can be calculated for an individual compartment from the energy and mass balance equations with respect to the size, geometry and ventilation of the compartment, and to the thermal properties of the enclosing structure [15], [16], [20], [22] -[33]. These compartment effects are characterized by the so-called "opening factor", $A_w \sqrt{h_w}/A_t$, and the coefficient, K_f, where A_w is the area and h_w the mean height of the ventilation openings and K_f is given in table II.3 for different thermal properties of the enclosing structures.

As a simplification, post-flashover compartment fires can be divided into two types of behaviour - ventilation controlled or fuel controlled, [22] . For the first type, the combustion during the active stage of the fire is controlled by the ventilation of the compartment with the burning rate approximately proportional to the air supply through the openings of the fire compartment and not in any decisive way dependent on the amount, porosity and particle shape of the fuel. For the second type, the combustion is mainly controlled by the properties of the fuel (fire load) and is largely independent of the air supply through the openings. The boundary between the two kinds of compartment fires is not clearly marked.

The practical use of the analytical models developed for the post-flashover compartment fire is facilitated by access to well documented computer programmes - cf., for instance [30]. A closed-form approximation, arranged to suit hand-calculations, is presented in [31].

The ability of the models is illustrated in figure II.1 and II.2. In figure II.1, a set of full-line curves is reproduced from a Japanese full-scale test, showing the temperature-time curves of the combustion gases at different points in the fire compartment [34]. The dash-line curve shows the corresponding temperature-time relationship calculated by applying the analytical model derived in [25].



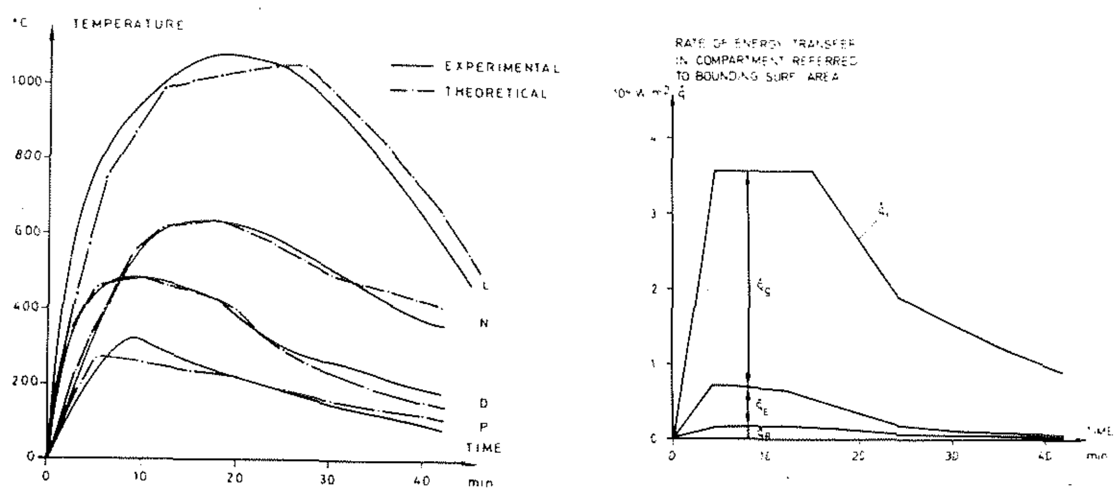
Experimentally determined time curves of the gas temperature at different points in a fire compartment (full-line curves) [34] , compared with a theoretical curve calculated according to the analytical model presented in [25] (dash-line curve). Fire load densiy q_t = 140 MJ x m^{-2}; fire compartment with opening factor $A_w\sqrt{h_w}/A_t$ = 0.0467 $m^{1/2}$ and bounding structures of concrete floor, concrete roof and walls made of hollow concrete blocks

Fig. II.1.

Figure II.2 shows the variation with time of the average gas temperature inside the fire compartment, measured in full-scale tests performed at the Fire Research Station in UK [35], compared with the corresponding curves obtained by the analytical model in [25] - cf. [27]. The figure also illustrates, for one of the tests, the proportions between the terms in the energy balance equation of the fire compartment

$$\dot{q}_t = \dot{q}_g + \dot{q}_E + \dot{q}_R \qquad \text{(II-3)}$$

where $\dot{q}_t$ = rate of heat release by combustion inside the compartments, $\dot{q}_g$ = rate of heat loss by convection through the openings, $\dot{q}_E$ = rate of heat loss through the bounding walls, floor and ceiling, and



Experimental variation with time of the average gas temperature inside a fire compartment (full-line curves) [35], compared with corresponding theoretical curves calculated according to the analytical model presented in [25] (dash-line curves). Fire load density q_t = 31 (test P), 62 (test D), 124 (test N) and 248 MJ x m^{-2} (test L); fire compartment with opening factor $A_w \sqrt{h}/A_t$ = 0.12 $m^{1/2}$ and bounding structures of concrete floor, refractory concrete ceiling and walls of common brick. The time curves for the different terms in the energy balance equation for test D are shown at the right [27]

<u>Fig. II.2.</u>

$\dot{q}_R$ = rate of heat loss by radiation through the openings. Generally speaking, the results shown verify that the applied analytical model is adequate for the simulation of experimental full-scale fires.

The available analytical models and computer programmes for the post-flashover compartment fire provide the basis for a systematized design. The gas temperature-time curves θ_t-t in figure II.3, [15], [16], [20], [25], are an example of such a design basis for use in an analytical design of load bearing structures and partitions exposed to a compartment fire. The curves are approved by the National Swedish Board of Physical Planning and Building for general practical application. They apply to a fire compartment with surrounding structures, made of a material with a thermal conductivity $\lambda_b = 0.81\ W \times m^{-1} \times {}^oC^{-1}$ and a heat capacity $\rho c_b = 1.67\ MJ \times m^{-3} \times {}^oC^{-1}$ which has $K_f = 1.0$, i.e. fire compartment type A. Such a surrounding material corresponds roughly to an average of brick, concrete and aerated concrete.

The gas temperature-time curves in figure II.3 have been computed from the energy and mass balance equations of the fire compartment under the following simplifying assumptions:

* the combustion of the fire load takes place entirely within the fire compartment,
* the fire process is ventilation controlled,
* the temperature θ_t is uniform within the fire compartment at any time t,
* the coefficient of heat transfer for the internal surrounding surface is uniform over each individual part of the surface at any time t, and
* the heat transfer to and through the surrounding structures is one-dimensional and except window and door openings, uniformly distributed for each type of structure.

The consequences of the assumptions are analysed in [15], [27] and [36], verifying their reasonableness as a basis for the calculation of the load bearing capacity of fire exposed structures and structural members.

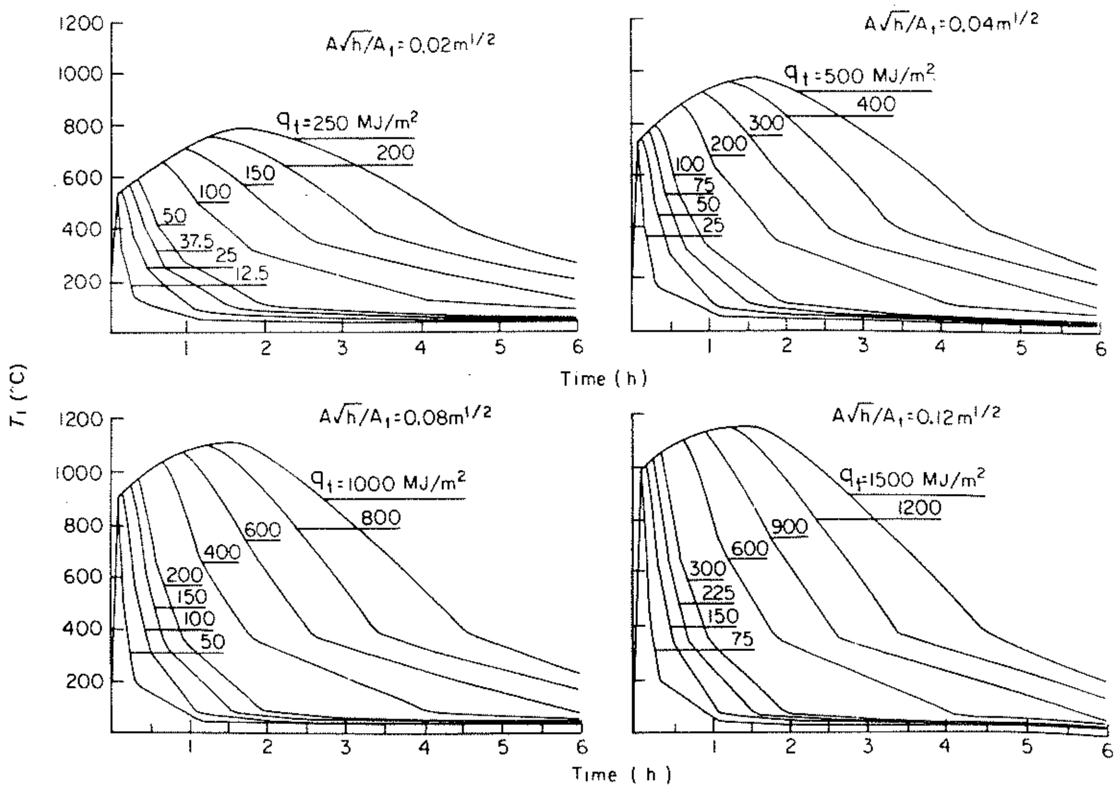
For fire compartments with surrounding structures, whose thermal properties are different from those of fire compartment, type A, an effective fire load density q_{tf} and an effective opening factor $(A_w\sqrt{h_w}/A_t)_f$ can be used in the heat balance, calculated from the real fire load density q_t and the real opening factor $A_w\sqrt{h_w}/A_t$ as follows [15], [16], [20]:

$$q_{tf} = K_f q_t \qquad \text{(II-4a)}$$

$$(A_w \sqrt{h_w}/A_t)_f = K_f A_w \sqrt{h_w}/A_t \qquad \text{(II-4b)}$$

where the coefficient K_f is given in table II.3 for seven types of fire compartment.

The gas temperature-time curves illustrated in figure II.3 are applicable to fire compartments of a size representative of dwellings, ordinary offices, schools, hospitals, hotels and libraries. For fire compartments with a very large volume - for instance, large industrial buildings and sports halls - the curves give an unsatisfactory description of the real fire exposure. For such types of buildings, it is confirmed by theory



Example of gas temperature-time curves θ_t-t of the post-flashover compartment fire for different values of the fire load density q_t and the opening factor $A_w \sqrt{h_w}/A_t$. Fire compartment, type A - from authorized Swedish Standard Specifications [20]

<u>Fig. II.3.</u>

and experience [37] that flashover will frequently not occur. This pre-flashover compartment fire can give a local fire exposure to a structural member - for instance, a beam, a column or a frame - more severe or less severe than that assumed for the post-flashover compartment fire illustrated in figure II.3. At present, there is no validated analytical model or design basis available for a determination of the fire exposure, which can be generally applied to fire compartments with a very large volume.

II.3.2 Standard Fire Exposure

In the majority of countries, the national requirements for fire engineering design of load bearing structural elements and partitions are directly related to the standard fire resistance test. In the design, the results of the tests have to meet the corresponding requirements specified in the building codes and regulations.

Fire resistance tests are carried out according to national specifications which vary only in minor details from country to country. In principle, the test conditions are in conformity with ISO Standard 834 [38].

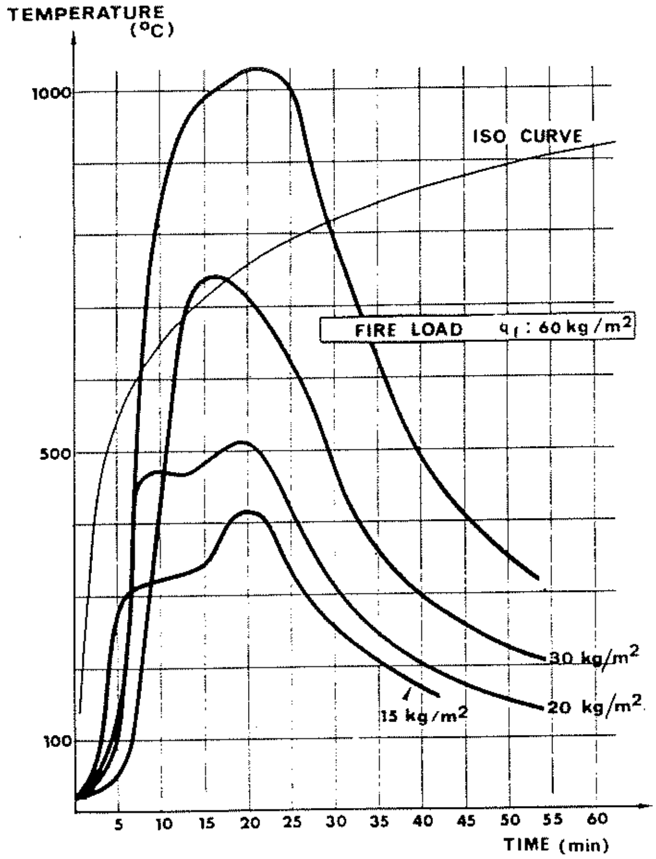
In the test, the specimen is exposed in a furnace to a temperature rise, which is controlled so as to vary with time within specified limits according to the relationship:

$$\theta_t - \theta_o = 345 \log_{10} (8t+1) \qquad \text{(II-5)}$$

where

t = time, in minutes,
θ_t = furnace temperature at time t, in ^oC, and
θ_o = furnace temperature at time t=0, in ^oC.

The temperature-time curve given by equation II-5 is shown in figure II.4 for $\theta_o = 20^oC$. For comparison, the figure also includes a set of curves giving the average gas temperature inside the fire compartment, obtained in full-scale tests carried out at the fire test station at Maizieres-les-Metz for four different fire load densities in a room with an opening factor



The standard fire according to equation II-5 (ISO curve), compared with the time curves of the average gas temperature determined in four full-scale experimental fires characterized by the same opening factor $A_w \sqrt{h_w}/A_t = 0.157\ m^{1/2}$ and a varying fire load density $q_f = 15, 20, 30$ and 60 kg wood per m^2 floor area [39]. Corresponding fire load density $q_t = 45, 60, 90$ and 180 MJ m^{-2}, respectively. Compartment with bounding structures of floor and one wall of light weight concrete, three walls of common brick and ceiling of refractory concrete - walls and ceiling insulated on the inside by a vermiculite based plaster

Fig. II.4.

$A_w\sqrt{h_w}/A_t = 0.157\ m^{1/2}$ [39]. The curves demonstrate that the thermal exposure in an experimental fire can deviate considerably from the thermal exposure in the standard fire.

Internationally, the standard fire resistance test is considered to be one of the most thoroughly understood test methods. In spite of this, the test can be criticized. In its present form, a number of features are not clearly defined. These include the heating and restraint characteristics, the environment of the furnace, and the thermocouples for measuring and regulating the furnace temperature. Consequently, a considerable variation may arise in the value of fire resistance measured for one and the same structural member, when tested in different laboratories, because the furnace characteristics and the support and restraint conditions of the test specimens may be different. See for instance [40] and [41].

The important progress, noted during the last ten years in the development of computation methods for an analytical structural fire engineering design, enables fire resistance to be determined by calculation for many practical applications. Consequently, more and more countries are accepting analytical classification of load bearing structural elements with respect to the standard fire as an alternative to testing. An important purpose of the ECCS-Recommendations is to stimulate more countries to accept this classification method officially and to facilitate the practical application of the procedure.

Irrespective of the fire resistance being determined analytically or by a test for a thermal exposure according to equation II-5, it is important to remember that the standard fire resistance test does not represent the real fire exposure in a building nor does it measure the behaviour of the structural element as a part of an assembly in a building. What the test or the corresponding calculations do is to grade structural elements and the building codes and regulations then require different grading levels of elements according to the circumstances.

The grading levels required depend on such influences as the occupancy, the building height and volume and the importance of the structure or structural element for the overall stability of the building. One of the factors included is the severity of fire exposure which might occur, specified as the standard fire duration t_d. This was first quantified by Ingberg who derived the relationship

$$t_d \sim Q/A_f = q_f \qquad \text{(II-6)}$$

which is still the basis of most current regulations. In later work, the importance of the ventilation and geometry of the compartment was also quantified, as described in section II.3.3.

When applying the standard fire duration t_d, it is essential to remember that it is only a test duration and not a real fire duration.

II.3.3 Equivalent Time of Fire Exposure

The concept of equivalent time of fire exposure was introduced as a way of relating a compartment fire exposure to the heating according to the standard fire - equation II-5. The concept can be used in practice, for instance, to give an improved classification for fire ranking or grading of structural elements. In principle, the equivalent time of fire exposure is defined as that length of the heating period in a standard fire which gives the same, critical effect on a structural element with respect to failure as the complete process of the compartment fire.

For steel structures, two alternative forms of the concept are given in the literature. The most simple one gives the equivalent time of fire exposure t_e as a function only of the parameters influencing the fire process. In a more developed form, the effect of the structural parameters is also included.

A simple formula, giving the equivalent time of fire exposure as independent of the structural parameters, was derived in [42] and [43] for protected steel structures as follows: A reference element was chosen, with thermal characteristics such that for a given experimental fire exposure it would attain a maximum steel temperature of a fixed value, e.g. 500 ^{o}C. The equivalent time of fire exposure t_e was then determined over the temperature-time curve of the standard fire for the same element to attain the same steel temperature. By repeating this procedure for different experimental fires, an empirical formula was obtained giving t_e as a function of only the fire load and the properties of the fire compartment. A similar, but generalized approach, based on the compartment fire exposure illustrated in figure II.3, as presented in [44] and [45], gives the following approximate formula:

$$t_e = 0.067 \frac{q_{tf}}{\left(\frac{A_w\sqrt{h_w}}{A_t}\right)_f^{\frac{1}{2}}} \qquad (min) \qquad \text{(II-7a)}$$

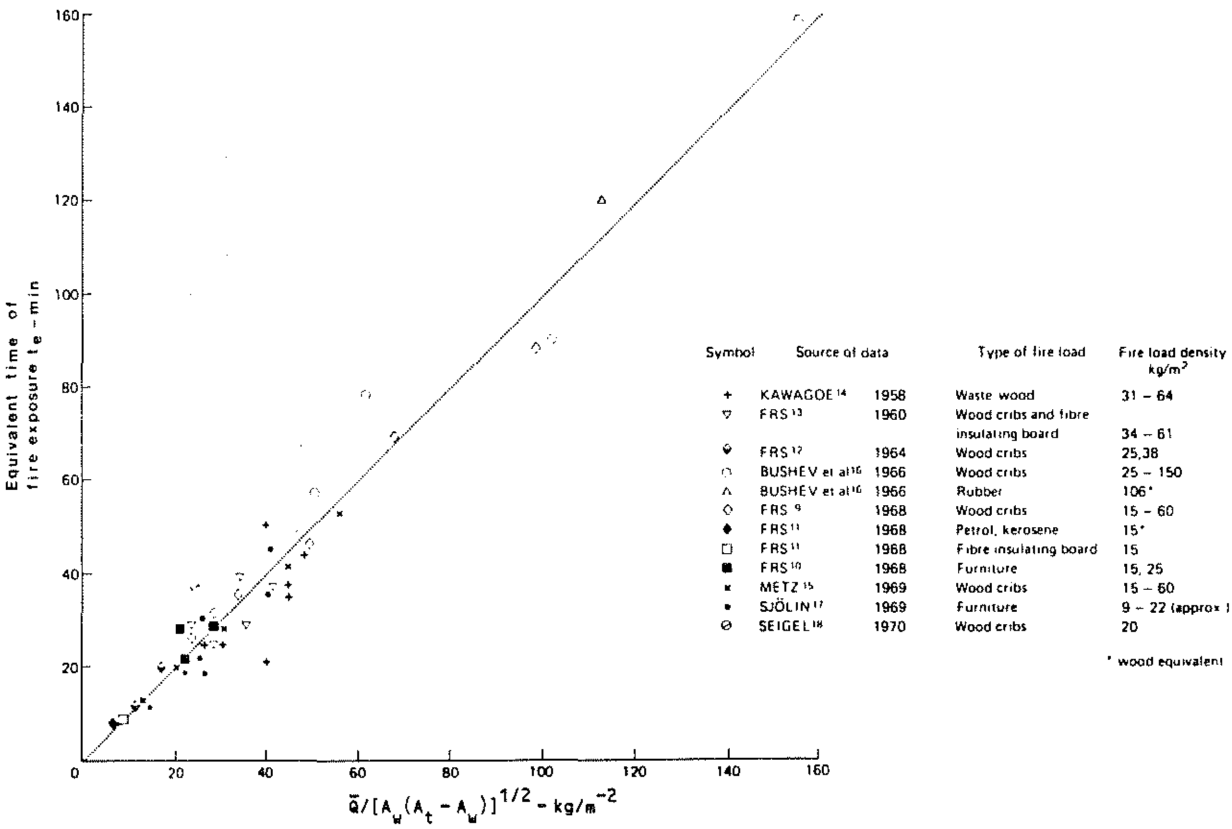
in which q_{tf} is the effective fire load density per unit area of the surfaces bounding the fire compartment (MJ x m^{-2}) and $(A_w\sqrt{h_w}/A_t)_f$ the effective opening factor of the fire compartment ($m^{1/2}$), calculated according to equation II-4 and table II.3. In this form, the formula can take into account the influence of varying thermal properties of the surrounding structures of the fire compartment.

Alternatively, equation II-7a can be written as

$$t_e = 0.067 \frac{q_{ff} A_f}{A_t \left(\frac{A_w \sqrt{h_w}}{A_t}\right)_f^{\frac{1}{2}}} \quad \text{(min)} \qquad \text{(II-7b)}$$

with $q_{ff} = K_f q_f$ = the effective fire load density per unit floor area ($MJ \times m^{-2}$).

Figure II.5 demonstrates the validity of equation II-7 for protected structural steel members [42]. In the figure, the symbols give values of the equivalent time of fire exposure t_e as a function of $\overline{Q}/[A_w(A_t-A_w)]^{1/2}$, based on gas temperature--time curves determined in experimental fires in larger-scale brick and concrete compartments. $\overline{Q}$ is the total fire load expressed as the equivalent weight of wood in kg. The tests comprise different types of fire



Equivalent time of fire exposure t_e as a function of $\overline{Q}/[A_w(A_t-A_w)]^{1/2}$, derived for insulated steel elements from experimental fires in larger-scale brick and concrete compartments. $\overline{Q}$ is the total fire load in kg wood equivalent [42]

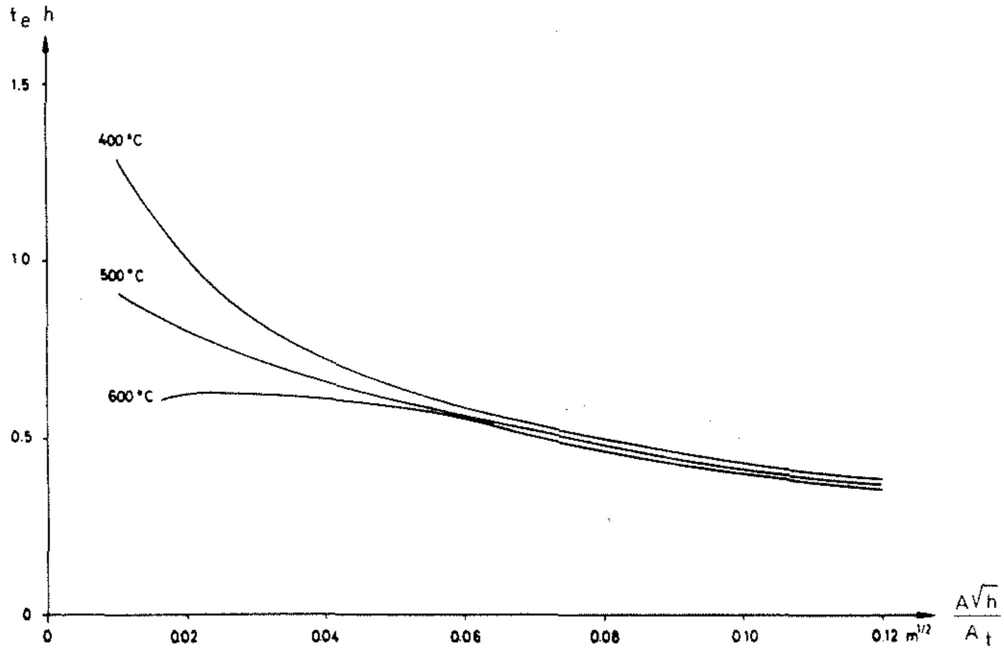
Fig. II.5.

loads according to the table included in the figure with a range for the fire load density q_f from 9 to 150 kg wood equivalent per m^2 floor area. For frequent values of the opening height h_w and the quotient $(A_t-A_w)/A_t$, the straight line in figure II.5 gives values of the equivalent time of fire exposure t_e which are in reasonable agreement with the values obtained by equation II-7.

As the formulae according to equation II-7 are derived from the gas temperature-time curves in figure II.3, this agreement indirectly demonstrates that these curves are a reasonable basis for a fire engineering design of load bearing structures and structural members.

The formulae given by equation II-7 and the relationship shown in figure II.5 are based on a critical steel temperature of 500^oC. The influence on the equivalent time of fire exposure of varying the value of the critical steel temperature is illustrated in figure II.6 for protected steel elements, fire exposed according to figure II.3 at a fire load density $q_t = 125$ MJ x m^{-2} [44] . The figure shows that the influence on t_e of variations in the critical steel temperature is considerable for low values of the opening factor $A_w \sqrt{h_w}/A_t$. For $A_w\sqrt{h_w}/A_t > 0.05$ $m^{1/2}$, this influence is comparatively small. A similar effect is noted for unprotected structural steel elements.

Summarizing, the formulae of equation II-7 have been shown to be applicable to fire exposed unprotected and protected structural steel elements, with a critical steel temperature of about 500^oC and they can also be used for other values of the critical steel temperature, provided that the opening factor of the fire compartment $A_w\sqrt{h_w}/A_t > 0.05$ $m^{1/2}$. For smaller values of the opening factor, an improved design basis is given in Appendix A, showing the equivalent time of fire exposure t_e as dependent on the section factor as well as the parameters influencing the fire process.



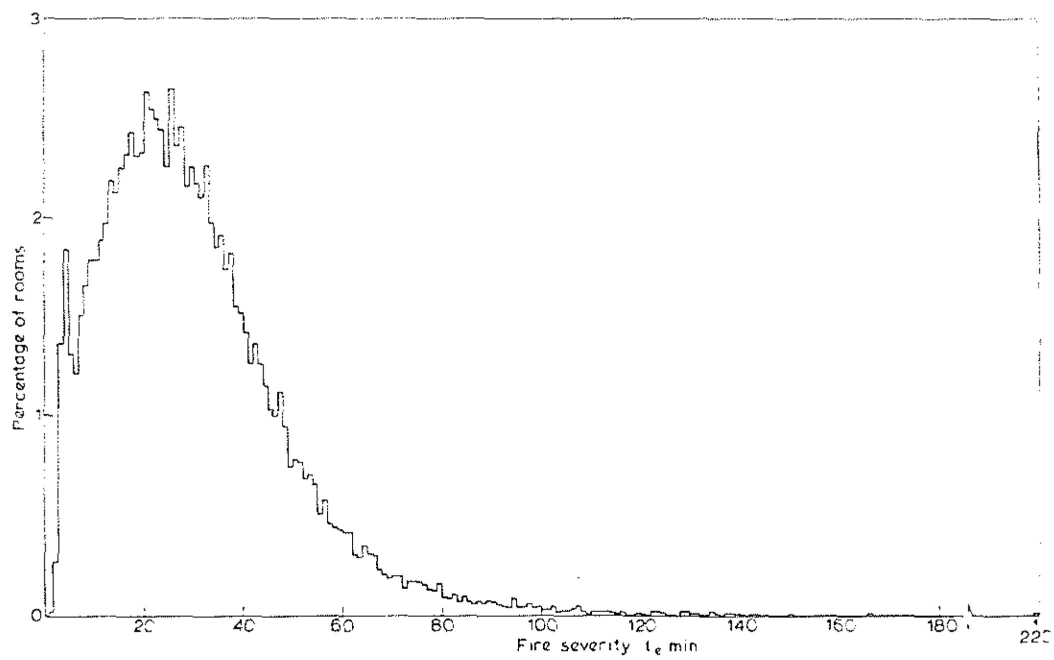
The influence on the equivalent time of fire exposure t_e *of varying level of the critical steel temperature* for protected steel elements. Compartment fire exposure according to figure II.3; fire load density q_t = 125 MJ m^{-2} [44]

Fig.II.6

Although the equivalent time of fire exposure relates the compartment fire exposure and the heating according to the temperature-time curve of the standard fire, the concept does not give any useful information on, for instance, the expected rate of heating or real duration of the real fire. In addition, the formulae derived may not be applicable to large fire compartments and will have the same limitations already discussed in relation to the gas temperature-time curves of the post-flash-over compartment fire reproduced in figure II.3.

In combination with statistical data, the equivalent time of fire exposure can be used to describe the fire severity for different types of fire compartments.

Figure II.7 illustrates this application of the concept [46]. The figure gives the frequency distribution of the fire severity, expressed as the equivalent time of fire exposure t_e in intervals of one minute, and estimated by a Monte Carlo simulation from data, obtained from statistical surveys of modern office rooms. At the simulation, t_e was defined by a formula determined by the straight line in figure II.5.



Frequency distribution of the fire severity, expressed as the equivalent time of fire exposure t_e, for modern office rooms, obtained by simulation [46]

Fig. II.7.

As mentioned in the introduction, an analytical structural design for a compartment fire can be integrated with a probabilistic model. Various levels of ambition can then be distinguished. For ordinary applications, however, such a probability based structural fire design must follow a simplified approach according to a practical design format calculation, specifying characteristic values and related partial safety factors for the action effects and the response capacities.

For a fire design, related to the equivalent time of fire exposure t_e, the practical design format can be given in the following form [2], [8]:

$$\frac{t_{fr}}{\gamma_f} \geq \gamma_n \gamma_e t_e \qquad \text{(II-8)}$$

in which t_{fr} is the fire resistance of the structural element - determined either experimentally by a standard fire resistance test or by calculation - and γ_f, γ_e, are partial safety factors, related to the fire resistance t_{fr} and the equivalent time of fire exposure t_e, respectively, and γ_n is an adaption factor accounting for the consequences of a structural failure (different safety classes) and special fire fighting provisions, for instance, the effect of a sprinkler system or the efficiency of the fire brigade actions. The partial safety factor γ_e then covers the uncertainties of the fire load density and the fire compartment characteristics, including the uncertainties of the analytical model for a determination of the fire exposure. The partial safety factor γ_f accounts for the uncertainties of the mechanical load and the thermal and mechanical material properties of the structural element, including the uncertainties of the analytical models for a determination of the load effect, the temperature state and the load bearing capacity, if the fire resistance is evaluated analytically.

The appropriate design load for evaluating the fire resistance of the structural element may be determined by considering the following accidental combination:

$$G + \Sigma\, \psi_i Q_{k,i} \qquad \text{(II-9)}$$

wherein

G = permanent loads,

$Q_{k,i}$ = variable loads (characteristic value),

ψ_i = combination coefficients.

The load combination formula implies that the partial safety factors $\gamma_G = 1.0$ and $\gamma_{Qi} = 1.0$. Example values of the combination coefficients ψ_i can be found in the EUROCODE publication (1984).

The detailed practical application of this probabilistic approach is given in [2] and [8].

Table II.1: Net calorific value H in MJ x kg^{-1} of some solid, liquid and gaseous materials

1. Solids

Anthracite	32-36	Melamine resin	19
Asphalt	40	Phenol-formaldehyde	28
Cellulose	15	Polyester	30
Charcoal	30	Polyester, fibre reinforced	21
Clothes	17-21	Polyethylene	47
Coal	29	Polystyrene	42
Coke	28-34	Polyurethane	24
Cork (grade SP)	35	Polyurethane-foam	25-29
Cork (grade F)	31	Polyvinyl chloride	18
Cotton	18	Urea-formaldehyde	18
Grain	17	Urea-formaldehyde foam	12-15
Grease	40	Rubber	
Kitchen refuse	8-21	Foam rubber	32
Leather	20	Gutta-percha	45
Linoleum	21	Rubber waste	21
Paper, cardboard	16-18	Silk	17-21
Paraffin wax	47	Straw	17
Plastics		Wood	17-20
ABS-plastics	40	Wool	23
Acrylic plastics	27		
Celluloid	19		
Epoxy	34		

The above values apply to materials in a dry state. The calorific value of moist materials H_F can be determined from the formula $H_F = H(1-0.01m)-0.025m$, where m is the moisture content in % by weight.

2. Liquid

Crude oil	43	Paraffin oil	41
Diesel oil	41-42	Petrol	44
Linseed oil	39	Spirits	33-34
Methanol	23	Tar	38

3. *Gases* (H in MJ/m^3n)

Acetylene	57	Coal gas	17
Butane	110	Hydrogen	140
Carbon monoxide	13	Propane	86

Table II.2a: Fire load density q_t per unit area of the surface bounding the fire compartment, according to recent Swedish investigations. q_t according to equation II-1b [15],[16]

Type of fire compartment	Average $MJ\cdot m^{-2}$	Average $\{Mcal\cdot m^{-2}\}$	Standard deviation $MJ\cdot m^{-2}$	Standard deviation $\{Mcal\cdot m^{-2}\}$	Characteristic value (0.8 fractile) $MJ\cdot m^{-2}$	Characteristic value (0.8 fractile) $\{Mcal\cdot m^{-2}\}$
1 Dwellings 1)						
1a Two rooms and a kitchen	150	{35.8}	24.7	{5.9}	168	{40.0}
1b Three rooms and a kitchen	139	{33.1}	20.1	{4.8}	149	{35.5}
2 Offices 2)						
2a Technical offices	124	{29.7}	31.4	{7.5}	145	{34.5}
2b Administrative offices	102	{24.3}	32.2	{7.7}	132	{31.5}
2c All offices, investigated	114	{27.3}	39.4	{9.4}	138	{33.0}
3 Schools 2)						
3a Schools - junior level	84.2	{20.1}	14.2	{3.4}	98.4	{23.5}
3b Schools - middle level	96.7	{23.1}	20.5	{4.9}	117	{28.0}
3c Schools - senior level	61.1	{14.6}	18.4	{4.4}	71.2	{17.0}
3d All schools, investigated	80.4	{19.2}	23.4	{5.6}	96.3	{23.0}
4 Hospitals	116	{27.6}	36.0	{8.6}	147	{35.0}
5 Hotels 2)	67.0	{16.0}	19.3	{4.6}	81.6	{19.5}

1) Floor covering excluded

2) Only moveable fire load components included

Table II.2b: Fire load density q_f per unit floor area, according to [21] . Characteristic values (0.8 fractile), calculated on the basis of the same statistical survey as used for the values in table II.2a. q_f according to equation II-1a

Type of fire compartment	Characteristic value (0.8 fractile) $MJ \times m^{-2}$	$(Mcal \times m^{-2})$
1 Dwellings		
1a Bedroom	630	(150)
1b Living-room	510	(120)
2 Offices		
2a Technical offices	720	(170)
2b Administrative offices	640	(155)
3 Schools		
3a Schools - junior level	370	(90)
3b Schools - middle level	400	(95)
3c Schools - senior level	260	(60)
4 Hospitals - bedroom	80	(20)
5 Hotels - bedroom	420	(100)

Only movable fire load components included

Table II.2c: Fire load density q_f per unit floor area, equation II-1a, for various types of fire compartments in German office buildings, according to [13]

Type of fire compartment	Average MJ·m^{-2}	{Mcal·m^{-2}}	Standard deviation MJ·m^{-2}	{Mcal·m^{-2}}
Company management	272	{64.8}	126	{30}
Production management	355	{84.8}	168	{40}
Officials	441	{105}	250	{60}
Office staff	417	{99.6}	210	{50}
Special rooms	1172	{280}	798	{190}
Technical rooms	278	{66.4}	109	{26}
Rooms of communication	168	{40}	240	{57}
All types of compartments	411	{98}	334	{80}

Only moveable fire load components included. In [13], the fire load density is given in kg wood per m^2. The values, given in the table, are based on a net calorific value of wood $H = 4$ Mcal x kg^{-1}

Table II.3: Coefficient K_f for transforming a real fire load density q_t and a real opening factor of a fire compartment $A_w\sqrt{h_w}/A_t$ to an effective fire load density q_{tf} and an effective opening factor $(A_w\sqrt{h_w}/A_t)_f$ corresponding to a fire compartment, type A - equation II-4

$q_{tf} = K_f q_t$ $\quad (A_w\sqrt{h_w}/A_t)_f = K_f\ A_w\sqrt{h_w}/A_t$

Type of fire compartment	Opening factor $A_w\sqrt{h_w}/A_t$ $m^{1/2}$					
	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)	1.00-0.50	1.00 0.50	0.80-0.50	0.70-0.50	0.70-0.50	0.70-0.50
Type G	1.50	1.45	1.35	1.25	1.15	1.05
Type H	3.00	3.00	3.00	3.00	3.00	2.50

1) The lowest value of K_f applies to a fire load density q_t >500 MJ x m^{-2}, the highest value to a fire load density q_t<60 MJ x 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 A: Bounding structures of a material with a thermal conductivity $\lambda_b = 0.81$ W m^{-1} $^oC^{-1}$ and a heat capacity $\rho c_b = 1.67$ MJ m^{-3} $^oC^{-1}$.

Fire compartment, type B: Bounding structures of concrete.

Fire compartment, type C: Bounding structures of aerated concrete (density $\rho = 500\ kg\ m^{-3}$).

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

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

50% aerated concrete (density $\rho = 500\ kg\ m^{-3}$),
33% concrete, and
17%, from the interior to the exterior, of plasterboard panel (density $\rho = 790\ kg\ m^{-3}$) 13 mm in thickness, diabase wool (density $\rho = 50\ kg\ m^{-3}$) 10 cm in thickness, and 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 walls, and a concrete floor.

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

20% concrete, and
80%, from the interior to the exterior, of double plasterboard panel (density $\rho = 790\ kg\ m^{-3}$) 2 x 13 mm in thickness, air space 10 cm in thickness, and double plasterboard panel (density $\rho = 790\ kg\ m^{-3}$) 2 x 13 mm in thickness.

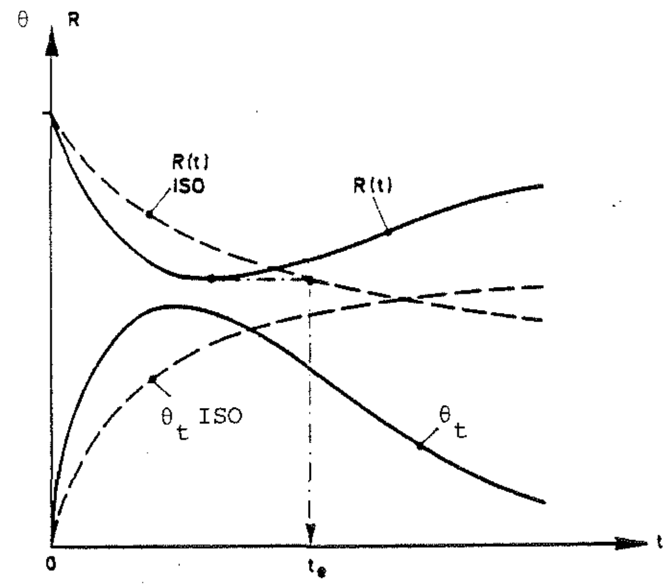
Fire compartment, type H: Bounding structures of sheet steel on both sides of diabase wool (density $\rho = 50\ kg\ m^{-3}$) 10 cm in thickness.

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_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_f, that alternative of interpolation is recommended which gives the lowest value of K_f. In determining K_f, it is not acceptable to combine types of fire compartments in such a way as to give a negative contribution to K_f.

APPENDIX A Accurate Form of Equivalent Time of Fire Exposure

As stated in section II.3.3, the equivalent time of fire exposure t_e is defined in principal as that length of the heating period in a standard fire which gives the same effect on a structural element with respect to failure as the complete process of the compartment fire.

This concept is illustrated in figure A1. The full-line curves show the variation with time of the gas temperature θ_t and the load bearing capacity R(t) of the structural element for a compartment fire exposure, determined by the fire load density q_t, the opening factor $A_w \sqrt{h_w}/A_t$ and the thermal properties of the structures bounding the fire compartment. The dash-line curves give the standard fire temperature-time variation θ_t, ISO, according to equation II-5 and the cor-

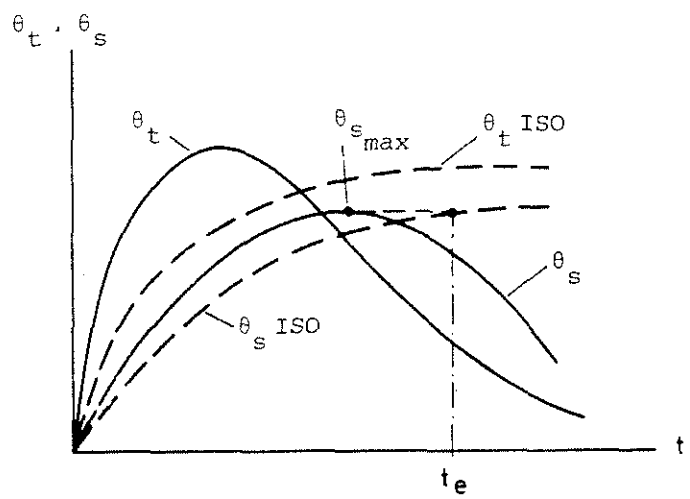


Definition of the equivalent time of fire exposure t_e. Full-line curves for a compartment fire exposure, dash-line curves for an exposure according to the standard fire ISO 834, equation II-5. θ_t is gas temperature and R(t) load bearing capacity

Fig. A1.

responding time curve of the load bearing capacity R(t), ISO. The minimum load bearing capacity of the structural element during the compartment fire is attained during the standard fire at the equivalent time of fire exposure t_e. The minimum load bearing capacity can be defined in three ways: as a critical value of a maximum deflection, a maximum rate of deflection or a maximum temperature.

For steel structures, it can normally be assumed that the minimum load bearing capacity is reached at the time for the maximum steel temperature θ_{smax}. The definition of the equivalent time of fire exposure t_e according to figure A1 can then be transferred to the definition shown in figure A2.



The equivalent time of fire exposure t_e as defined by the maximum steel temperature θ_{smax} of a fire exposed protected structural steel element. Full-line curves for a compartment fire exposure, dash-line curves for an exposure according to the standard fire, ISO 834, equation II-5. θ_t is gas temperature and θ_s steel temperature

Fig. A2.

A direct application of the definition according to figure A1 or A2 means that the equivalent time of fire exposure t_e depends on parameters influencing the fire process as well as on structural parameters. Figures A3 and A4 illustrate this in more detail for unprotected and protected steel structures, respectively [15],[16],[44].

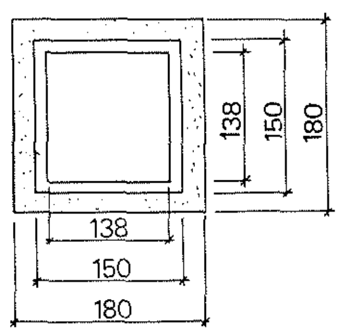
Figure A3 applies to unprotected steel structures assuming a compartment fire exposure according to figure II.3. The diagrams give the equivalent time of fire exposure t_e as a function of the fire load density q_t, the opening factor of the fire compartment $A_w\sqrt{h_w}/A_t$ and the structural parameter F/V. F is the fire exposed surface and V the volume of the steel structure per unit length. The resultant emissivity ε_r has been chosen as 0.5 for the heating according to the standard fire, in conformity with the ECCS-Recommendations, and alternatively as 0.5 and 0.7 for the compartment fire. With respect to practical applications, it can be estimated roughly that $\varepsilon_r = 0.7$ represents the conditions for a steel column within a fire compartment and $\varepsilon_r = 0.5$ the conditions for a steel beam. For a given value of t_e, the corresponding steel temperature θ_s can be calculated from equation III-8 in chapter III.

Figure A4 presents design curves giving the equivalent time of fire exposure t_e for protected steel structures as a function of the fire load density q_t, the opening factor of the fire compartment $A_w\sqrt{h_w}/A_t$ and the structural parameter $F_i\lambda_i/Vd_i$. F_i is the inside surface area of the protection per unit length of the structure, λ_i the thermal conductivity of the protecting material and d_i the thickness of the protection. For a given value of t_e, the corresponding steel temperature θ_s can be calculated from equation III-11 in chapter III.

By using effective values of the fire load density q_t and the opening factor $A_w\sqrt{h_w}/A_t$ according to equation II-4 and table II.3, the influence of varying thermal properties of the surrounding structures of the fire compartment can be taken into account in the determination of the equivalent time of fire exposure t_e from the diagrams in figures A3 and A4.

Example 1

A protected steel column has a cross section as shown in figure A5. The thermal conductivity of the insulation $\lambda_i = 0.12\ W \times m^{-1} \times {}^oC^{-1}$. The column is placed in a fire compartment, type B, with an opening factor $A_w\sqrt{h_w}/A_t = 0.047\ m^{1/2}$. The fire load density $q_t = 195\ MJ \times m^{-2}$, including floor covering.



Cross section of a protected steel column, fire exposed on four sides, Example 1. Dimensions in mm

Fig. A5.

Determine the equivalent time of fire exposure t_e and the corresponding maximum steel temperature θ_{smax}.

A transformation of the real fire load density q_t and the real opening factor $A_w\sqrt{h_w}/A_t$ to an effective fire load density q_{tf} and an effective opening factor $(A_w\sqrt{h_w}/A_t)_f$ according to equation II-4 and table II.3 gives

$K_f = 0.85$ (fire compartment, type B)

$q_{tf} = 0.85 \times 195 = 166\ MJ \times m^{-2}$

$$(A_w \sqrt{h_w}/A_t)_f = 0.85 \times 0.047 = 0.040 \ m^{1/2}$$

The inside surface area of the protection per unit length

$$F_i = 4 \times 0.15 = 0.60 \ m^2/m$$

The volume of the steel column per unit length

$$V = 0.15^2 - 0.138^2 = 3.46 \times 10^{-3} \ m^3/m$$

With the insulation thickness $d_i = 0.015$ m and thermal conductivity $\lambda_i = 0.12 \ W \times m^{-1} \times {}^oC^{-1}$ we have

$$\frac{F_i \lambda_i}{V d_i} = \frac{0.60 \cdot 0.12}{3.46 \cdot 10^{-3} \cdot 0.015} = 1387 \ W \cdot m^{-3} \cdot {}^oC^{-1}$$

For $(A_w \sqrt{h_w}/A_t)_f = 0.04 \ m^{1/2}$, $q_{tf} = 166$ $MJ \times m^{-2}$ and $F_i \lambda_i / V d_i = 1387 \ W \times m^{-3} \times {}^oC^{-1}$, the diagrams in figure A4 give

$$t_e = 0.88 \ h = 53 \ min$$

The corresponding steel temperature θ_s follows from equation III-11 in chapter III

$$\theta_s = 0.025 t_e \left(\frac{F_i \lambda_i}{V d_i}\right)^{0.77} + 140 = 0.025 \cdot 53 \cdot (1387)^{0.77} + 140 = 490^oC$$

A more rough estimation of t_e can be made from equation II-7a. Hence, it follows

$$t_e = 0.067 \frac{166}{(0.040)^{\frac{1}{2}}} = 56 \ min$$

Example 2

The fire resistance t_{fr} of a load bearing steel structure with a complicated mode of fire behaviour has been determined in a standard fire resistance test according to ISO 834. The structure then collapsed after $t_{fr} = 90$ min.

The structure had a cross section and was provided with an insulation, corresponding to $F_i \lambda_i / V d_i = 300$ W x m^{-3} x $^{o}C^{-1}$.

Check whether the structure will collapse or not in a design fire in a compartment, type A, with an opening factor $A_w \sqrt{h_w} / A_t = 0.02\ m^{1/2}$. The fire load density $q_t = 180$ MJ x m^{-2}.

From figure A4 we obtain

$t_e = 1.72$ h = 103 min

i.e. $t_e > t_{fr}$, which means that the structure will not survive in the compartment fire situation.

Equation III-11 in chapter III gives for the corresponding steel temperature

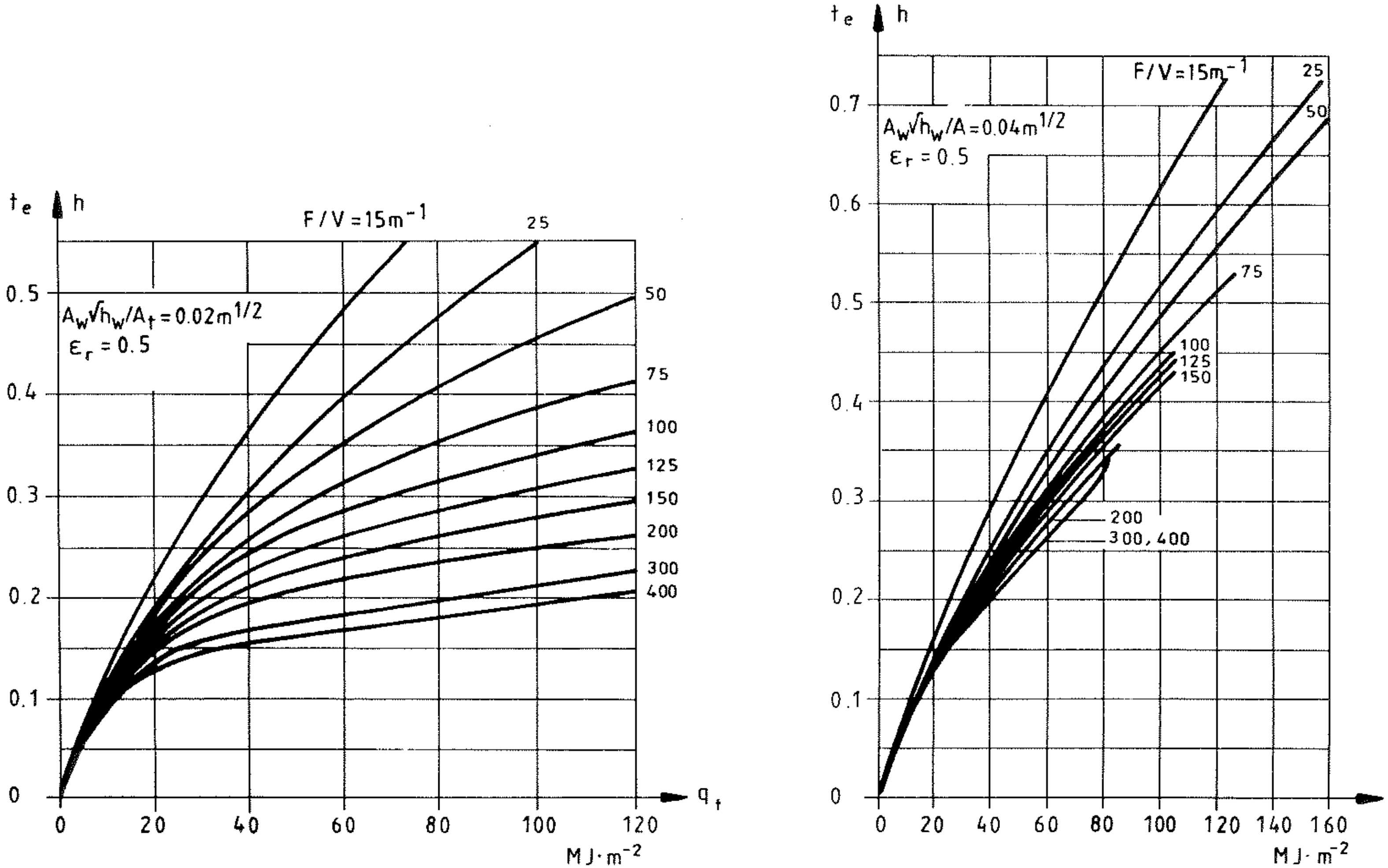
$$\theta_s = 0.025 t_e \left(\frac{F_i \lambda_i}{V d_i}\right)^{0.77} + 140 = 0.025 \cdot 103 \cdot (300)^{0.77} + 140 = 350^{o}C$$

An estimation of t_e from the formula according to equation II-7a gives

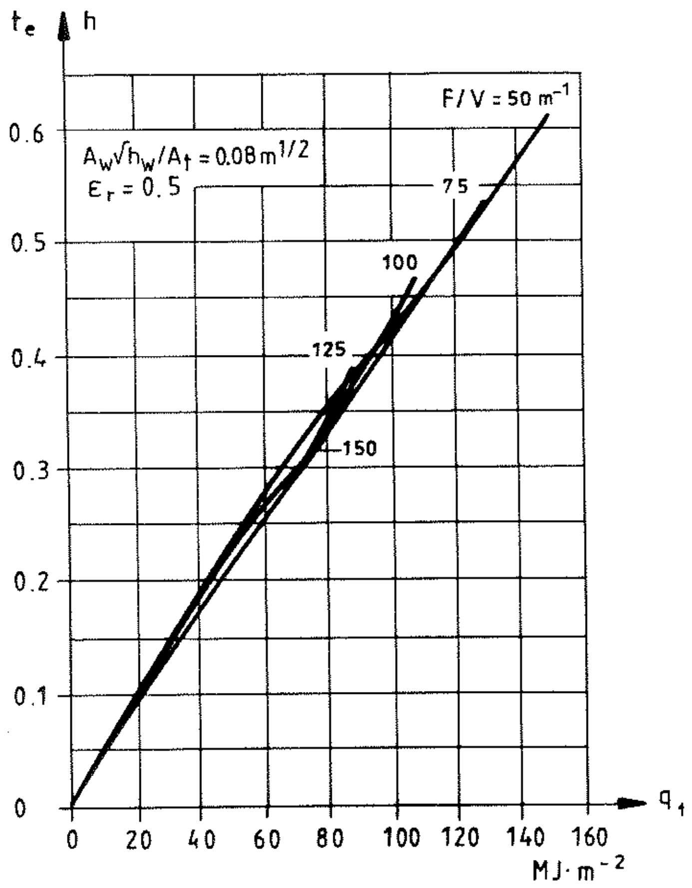
$$t_e = 0.067 \frac{180}{(0.02)^{\frac{1}{2}}} = 85 \text{ min}$$

i.e. a value which is about 17% on the unsafe side compared with the more accurate value determined from figure A4.

The results obtained in the two examples confirm the conclusions drawn from figure II.6.



Variation of equivalent time of fire exposure t_e of an unprotected steel structure with fire load density q_t, opening factor $A_w\sqrt{h_w}/A_t$ and structural parameter F/V. The curves are based on a compartment fire exposure according to figure II.3. By using effective values of q_t and $A_w\sqrt{h_w}/A_t$ according to table II.3, the influence of varying thermal properties of the surrounding structures of the fire compartment can be taken into account, [15], [16], [44]



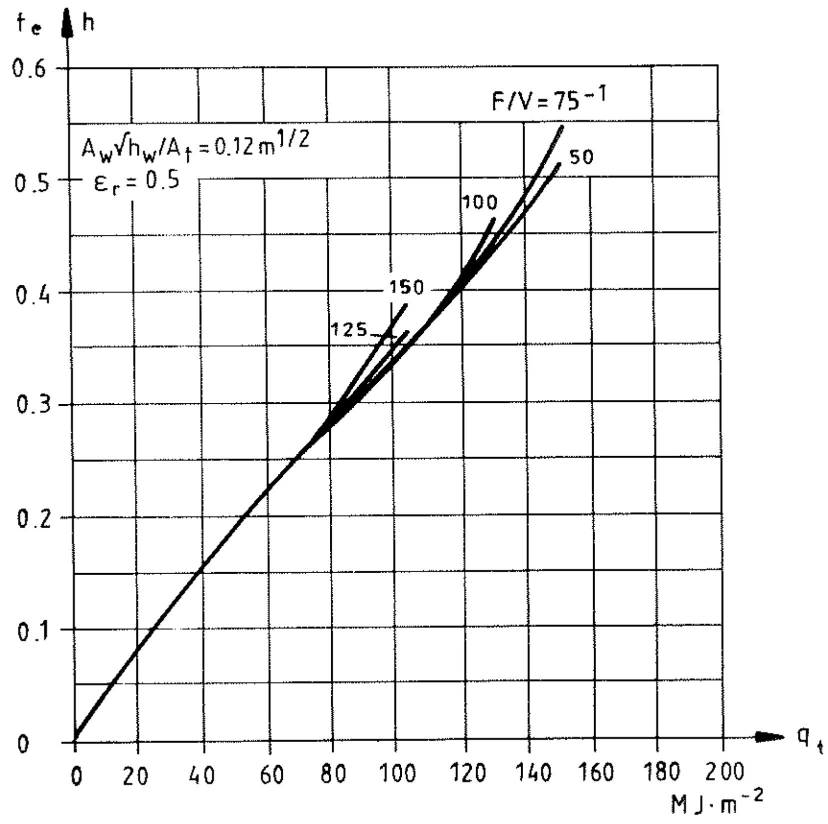


Figure A3: Cont.

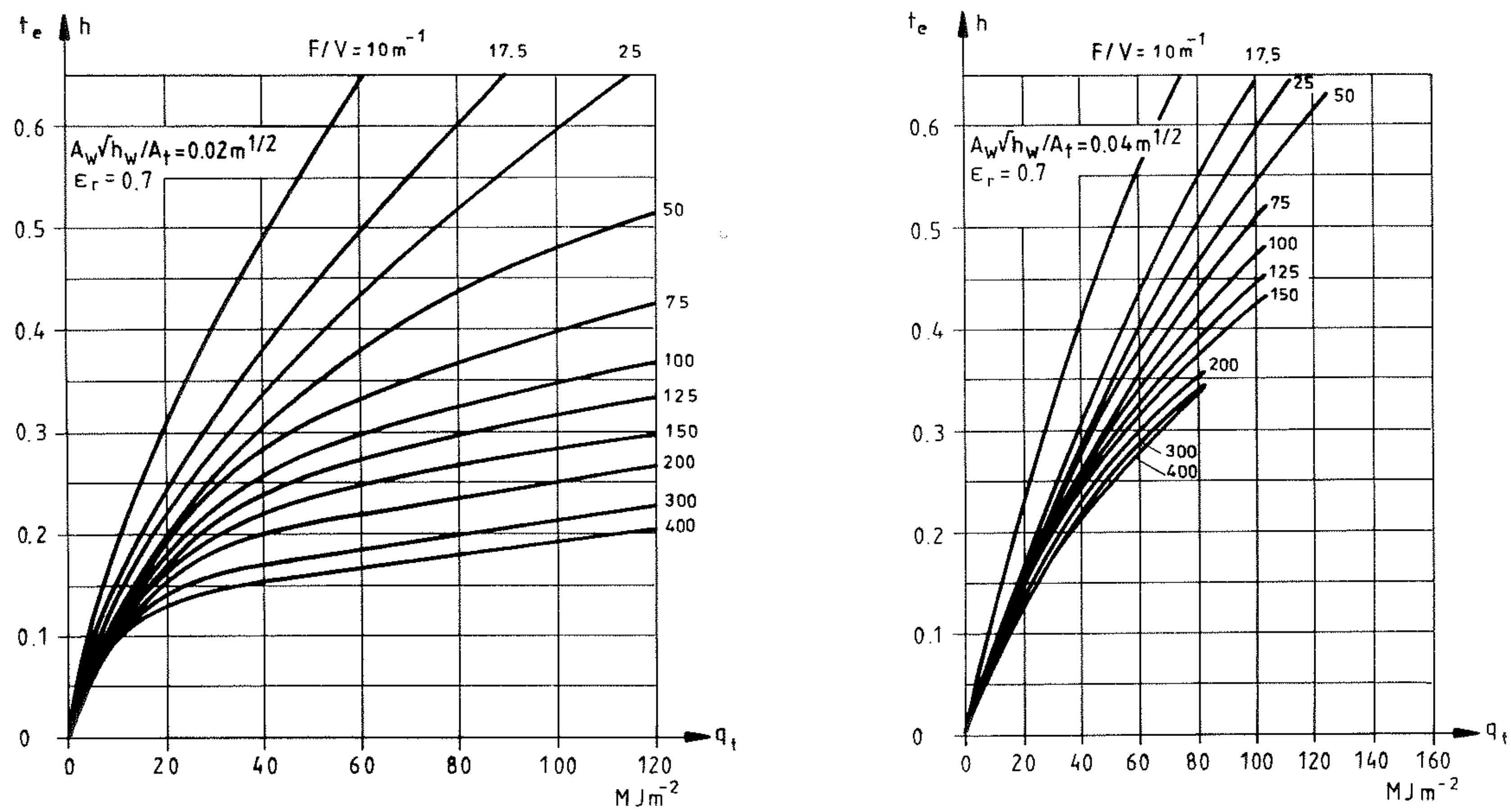


Figure A3: Cont.

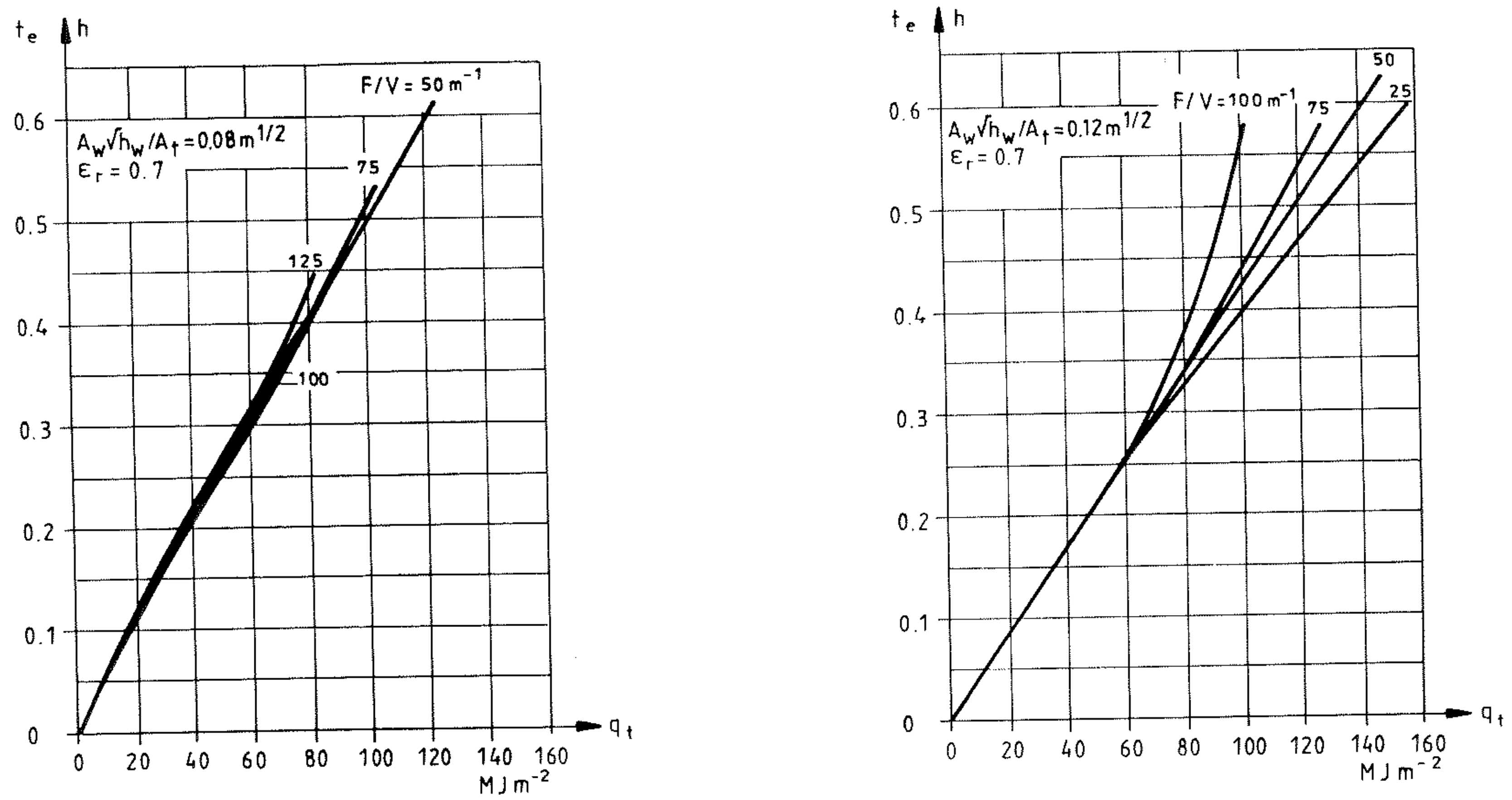
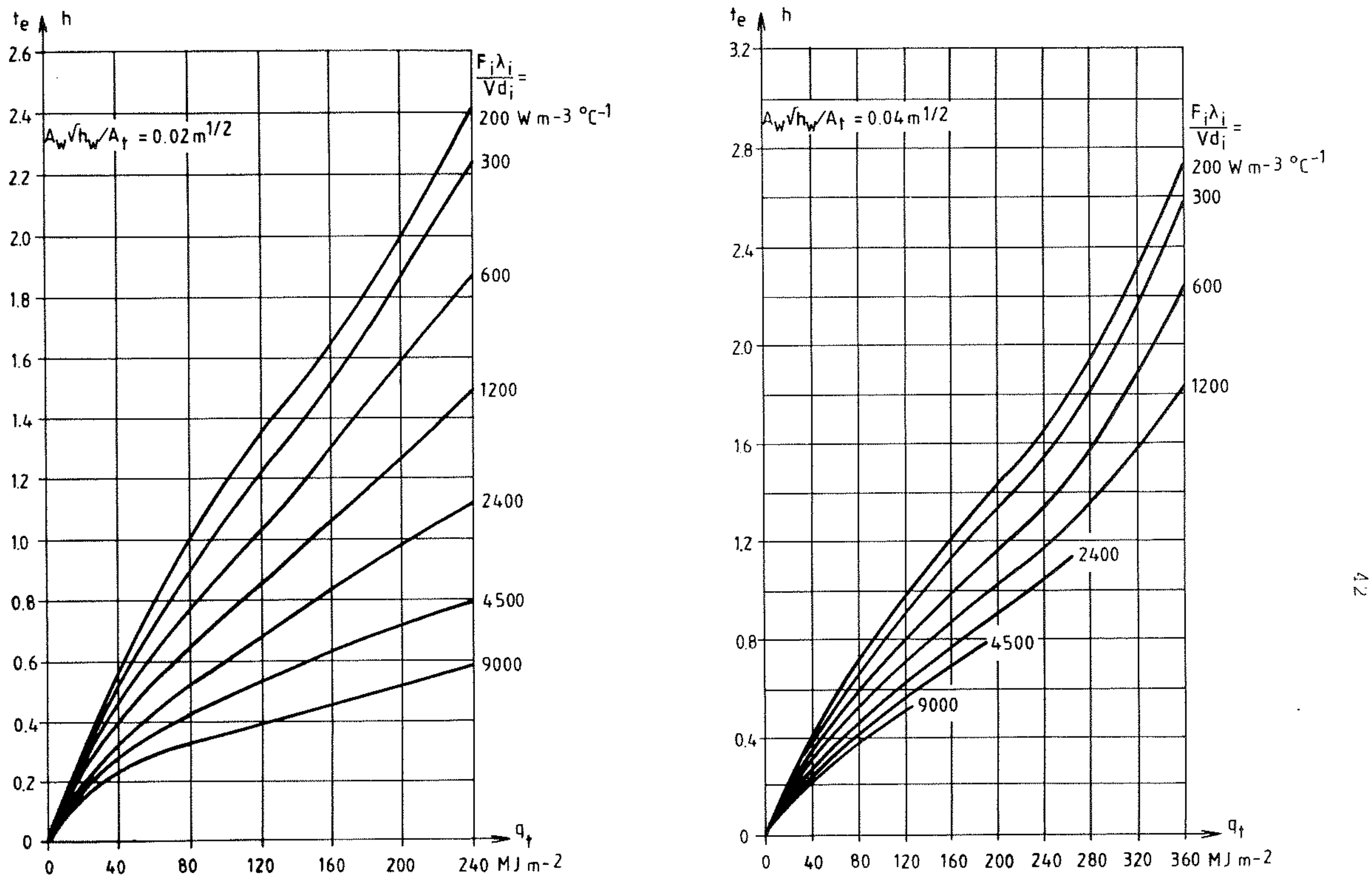


Figure A3: Cont.



Variation of equivalent time of fire exposure t_e of a protected steel structure with fire load density q_t, opening factor $A_w\sqrt{h_w}/A_t$ and structural parameter $F_i\lambda_i/Vd_i$. The curves are based on a compartment fire exposure according to figure II.3. By using effective values of q_t and $A_w\sqrt{h_w}/A_t$ according to table II.3, the influence of varying thermal properties of the surrounding structures can be taken into account [15], [16], [44]

Fig. A4.

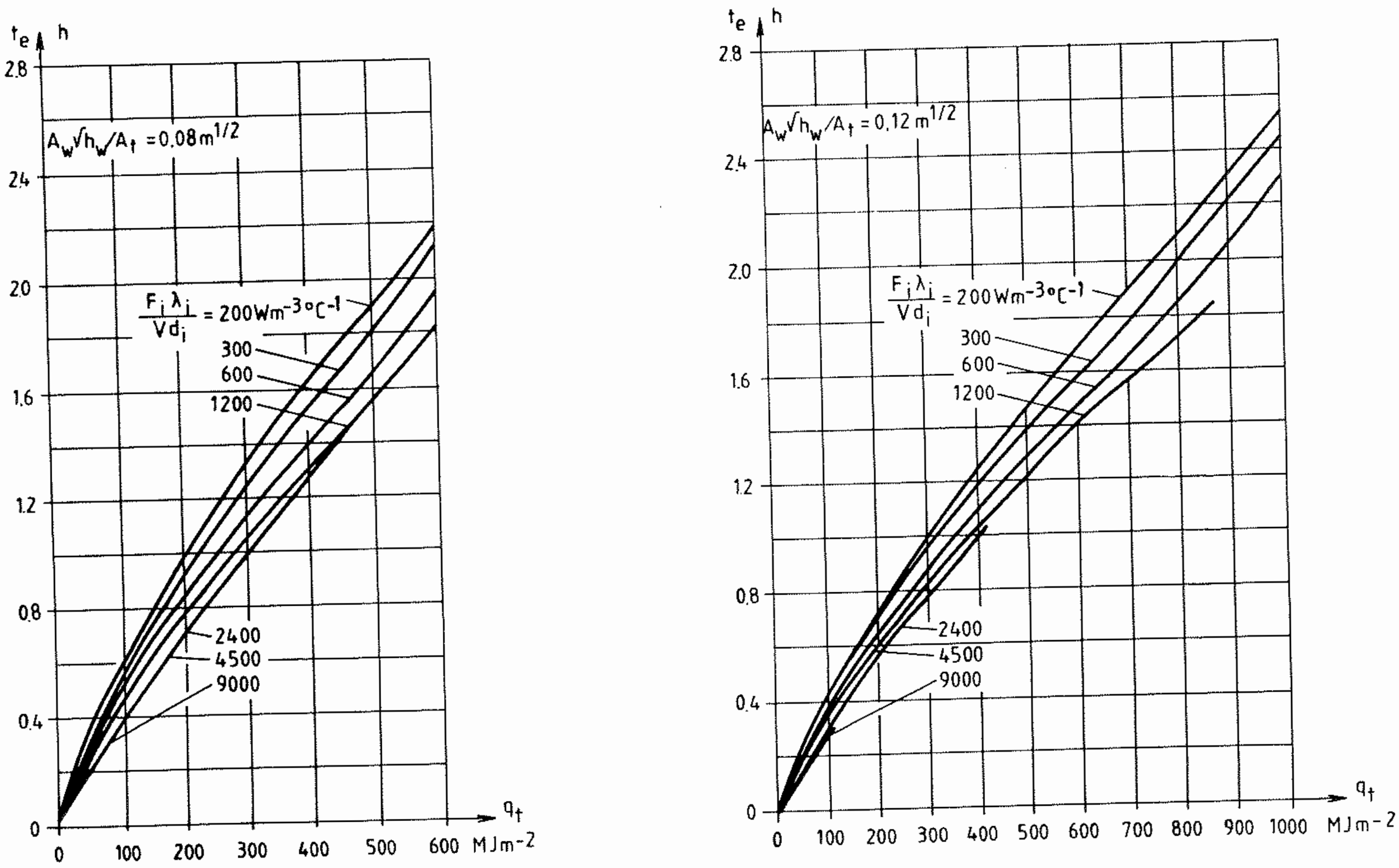


Figure A4: Cont.

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