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Pettersson, Ove

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NEED FOR AND SOME REMARKS ON INTERNATIONALLY STANDARDIZED FIRE TEST PROCEDURES[1)]

[1)] Originally presented at NFPA's First European Fire Conference
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NEED FOR AND SOME REMARKS ON INTERNATIONALLY STANDARDIZED FIRE TEST PROCEDURES

Ove Pettersson, Dr. Techn.
Professor in Structural Mechanics and
Concrete Construction
Civil Engineering Department
Lund University
Lund, Sweden

ABSTRACT

Introductory, the characteristics are given for on one side the conventional, highly schematic fire engineering design, connected to classification systems, and on the other side a differentiated fire engineering design procedure, directly based on performance criteria and functionally well-defined requirements. The two different approaches are compared for an application to load-bearing structures. From this background, the consequential need for standardized fire test procedures is analysed and some general conclusions are drawn. Parallelly, fundamental requirements on internationally standardized fire test procedures - for classification or more general purposes - are presented and summarily discussed, as regards applications to existing ISO recommendations and to a differentiated fire engineering design. Finally, the concept equivalent time of fire duration is mentioned and fragmentarily exemplified as a mean of translation from a real fire exposure to the standard heating conditions in fire resistance tests.

TRENDS OF DEVELOPMENT OF FIRE ENGINEERING DESIGN METHODS

The different ISO recommendations concerning fire test procedures and the corresponding national standards have been developed mainly on the basis of classification requirements, stipulated in building codes and regulations. The recommendations and standards then have been drawn up with the fundamental aim that the test results are to be used as data for a fire engineering design, taking into account real conditions in practice as well as possible.

In the light of these facts, it seems natural to begin a discussion of the need for an international standardization of fire test procedures by a general survey of the present state and the trends of development of fire engineering codes, regulations and design methods.

For a long time back, a fire engineering design of buildings and elements of building construction ordinarily is characterized by a highly schematic procedure, based on undifferentiated classification systems with respect to combustibility and ignitability of materials, spread of flame and smoke production of surface layers, and fire resistance of structural elements. For a classification, each property then is determined in a standardized fire test with fixed heating conditions. In a fire engineering design, the results of such standard classification tests directly are to be compared with the corresponding requirements, specified in the codes and regulations.

Applied to a load-bearing structural element, the internationally conventional system of fire engineering design can be illustrated according to Figure 1 [1]. The building codes and regulations are giving a required time of fire duration, which depends on the occupation, the height and the volume of the building, and the importance of the structural element. The fire engineering design comprises a proof that the proposed structural element has a fire resistance time, determined in a standard fire resistance test, which exceeds the fire duration required.

At present, a clear trend can be seen of a development of the building codes and regualtions in many countries towards functionally more well-defined requirements. As a consequence, the need continuously increases of methods for a differentiated fire engineering design. As concerns load-bearing structures or structural elements, several such design methods also have been published during the last ten years.

Mainly, these methods can be referred to one of two different groups with respect to the use of the basic data of the process of fire development. Characteristic for the methods of the first group is a design procedure with the varying properties of a real fire development taken into account over an equivalent time of fire duration, connected to the heating according to the standard time-temperature curve. The methods of the second group are characterized by a design procedure, directly based on gastemperature-time curves of the complete process of a real fire development, specified in detail with regard to the influence of the fire load and the geometrical, thermal and ventilation properties of the fire compartment.

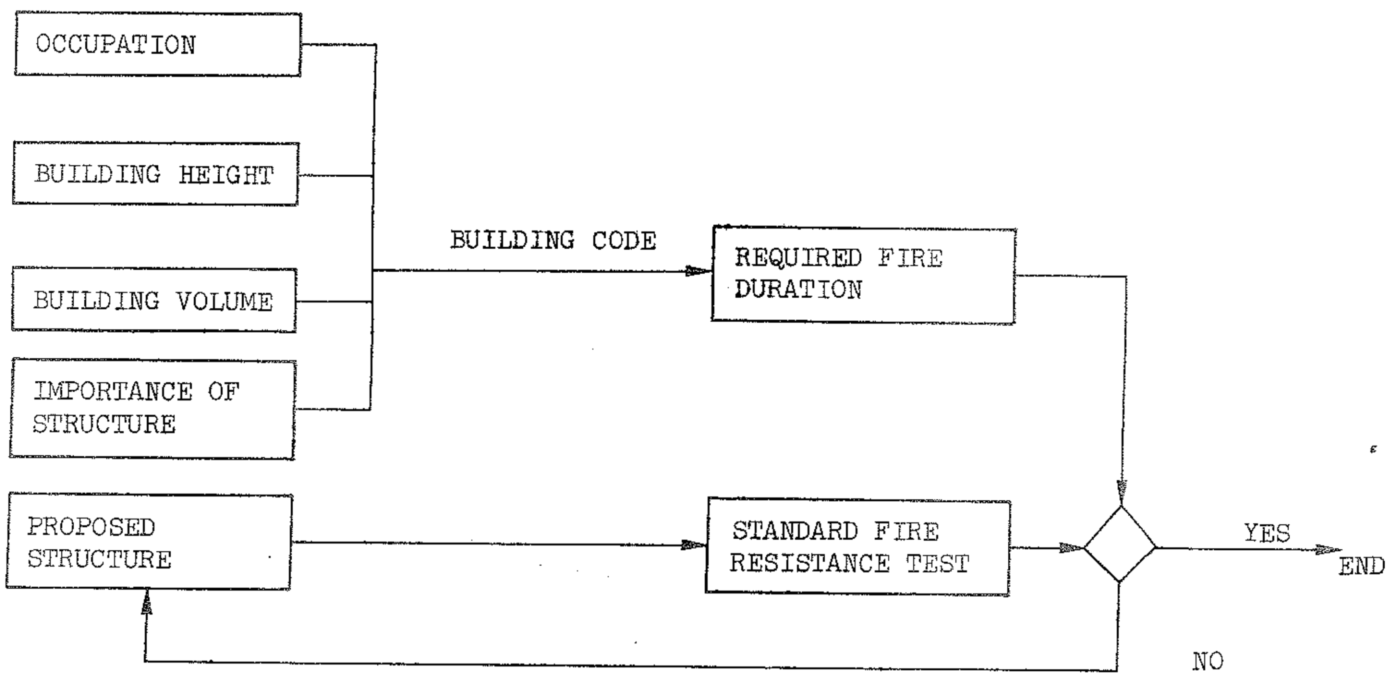

Figure 1. Conventional fire engineering design of load-bearing structural elements [1]

Such a design according to the second group methods comprises the following main components [2] to [5]:

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

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

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

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

(e) The application of the results according to (d) in a structural design, based on functional requirements and specifications on load and fire load levels, given in building codes and regulations.

The design procedure is shown more in detail in Figure 2.

The differentiated design system according to Figure 2 is to be seen primarily as a pure, theoretical procedure. The system can be applied in this way at present to, for instance, steel structures and isostatic, reinforced concrete beams and slabs. For these types of structures, now also design diagrams exist which considerably can facilitate a practical application. Fragmentary examples of such diagrams are given in Figure 3 and 4.

In Figure 3 [5], [6], then some design curves are presented, giving directly for a complete process of fire development the corresponding maximum steel temperature $\vartheta_{s_{max}}$ for an insulated steel structure at varying fire load q_t, and structural quotients U/F and d/λ_i. The curves are related to an opening factor of the compartment $A_v\sqrt{h}/A_t = 0{,}04\ m^{1/2}$. A_v is the opening area, h the opening height, and A_t the total interior surrounding surface of the compartment. U is the interior surface of the insulation per unit length, F the volume of the steel structure per unit length, d the thickness of the insulation, and λ_i the thermal

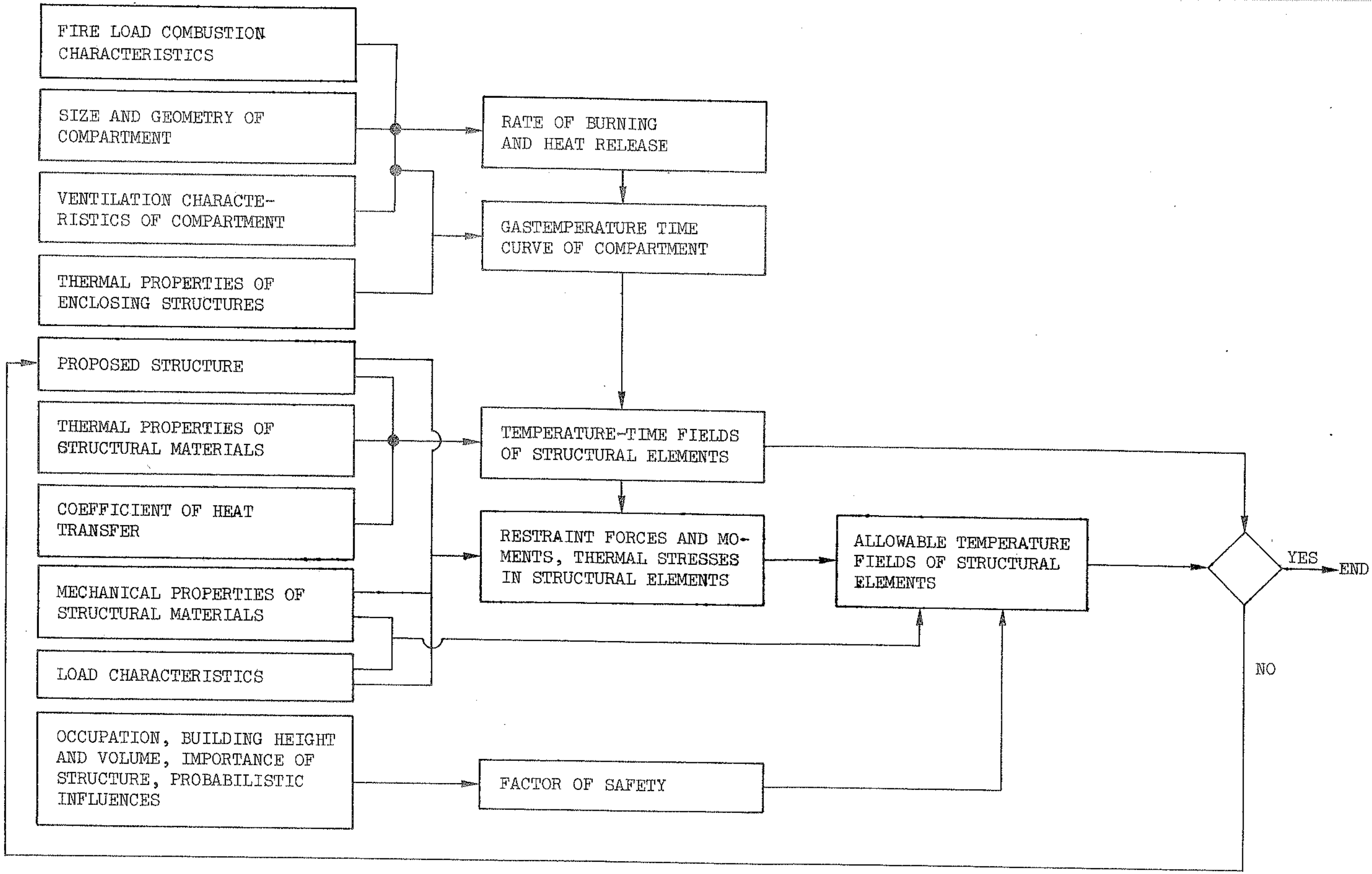

Figure 2. Differentiated fire engineering design of load-bearing structural elements [1] to [5]

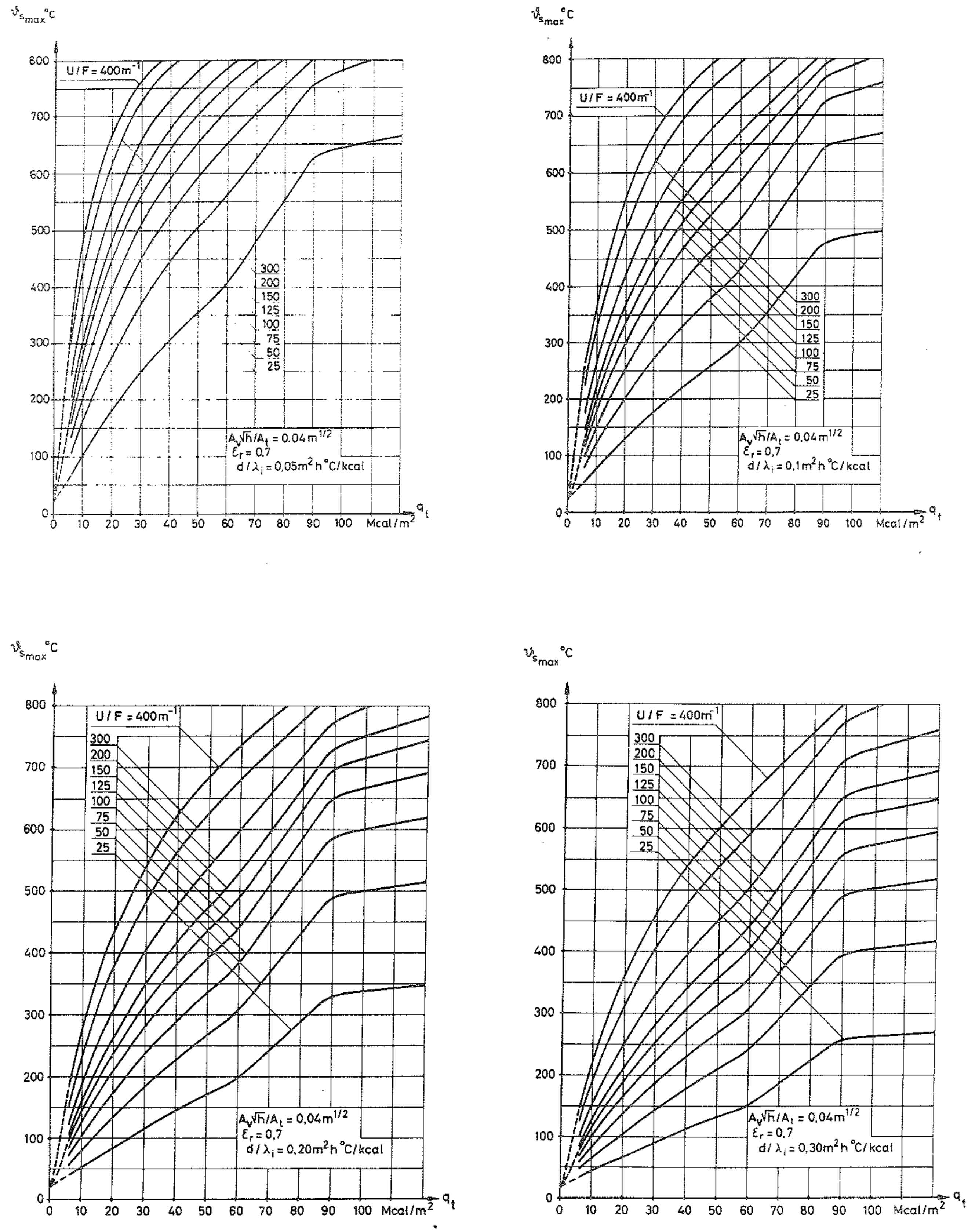

Figure 3. Maximum steel temperature $\vartheta_{s_{max}}$ for a fire exposed, insulated steel structure at varying fire load q_t and structural characteristics. Opening factor $A_v\sqrt{h}/A_t = 0.04\ m^{1/2}$ [5], [6]

conductivity of the insulation material. The fire load q_t is defined as the corresponding heat value per unit area of the surrounding surface A_t.

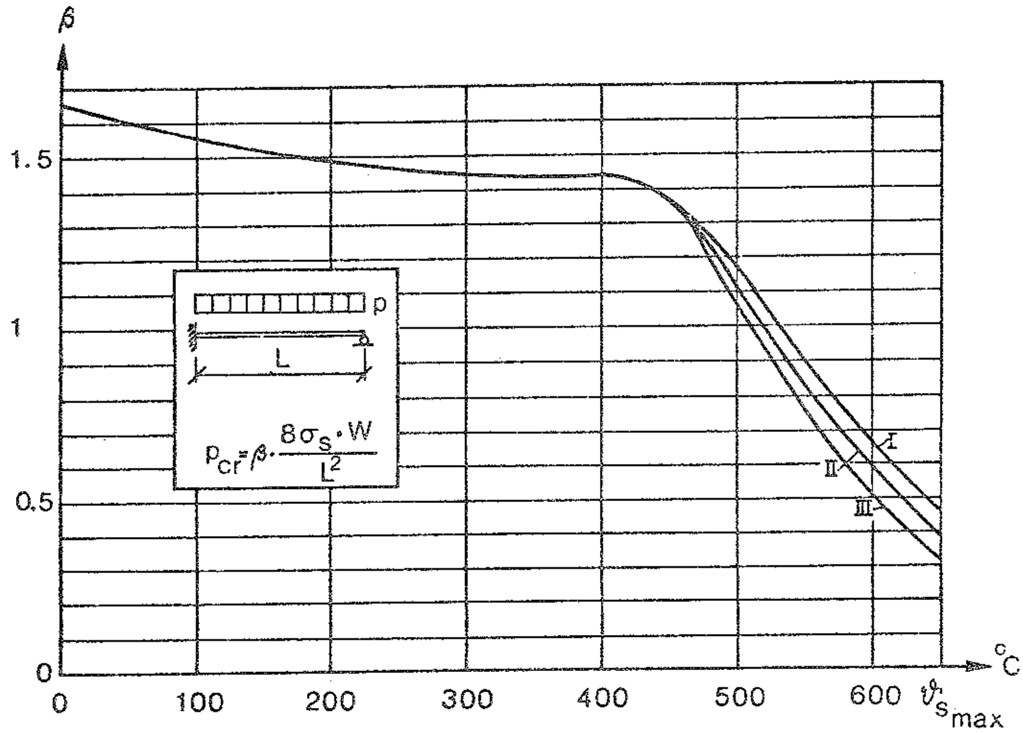

Figure 4. The critical load p_{cr} for a fire exposed steel beam with an I cross section, simply supported at one end and built-in at the other. Uniformly distributed load p [7]

Figure 4 [7] exemplifies another type of design diagrams, enabling a direct translation of the maximum steel temperature $\vartheta_{s_{max}}$ for a fire exposed steel structure to an adherent load-bearing capacity or critical load. The exemplified diagram applies to a steel beam with an I croos section, simply supported at one end and built-in at the other, acted upon by a uniformly distributed load p. In the formula for the critical load p_{cr}, σ_s denotes the yield point stress of the material at ordinary room temperature, and W the elastic modulus of resistance of the cross section. The curves I, II and III are connected to a rate of heating of 100, 20 and 4°C, respectively, and a rate of subsequent cooling, which is one third of the rate of heating.

CONSEQUENTIAL NEED OF STANDARDIZED FIRE TEST PROCEDURES.

GENERAL REQUIREMENTS AND REMARKS

In a conventional fire engineering design, based on classification systems, standardized fire test procedures are of primary importance. It is reasonable to assume, that this will be the case also in the future for a considerable time. By reason of that, the need of an international standardization of the test procedures is obvious. The need is further emphasized by the fact that the test procedures are comparatively expensive in many practical applications.

In pointing this out, it is essential to realize the development in progress towards a more differentiated approach to a fire engineering design, which will lead to a successively decreased importance of classification fire tests. Moreover, improved knowledge continuously will increase the possibilities to replace in a classification procedure parts of a fire test or a whole fire test by theoretical calculations. Such possibilities already exist for certain types of structures, for instance uninsulated or insulated steel beams, frames and columns.

In developing internationally standardized fire test procedures - for classification or more general purposes - certain fundamental requirements must be fulfilled. The most important requirements then are:

(a) A test method shall comprise a determination of either one single, well-defined physical, chemical or mechanical property or a more global, integrated effect, based on a number of relevant, well-defined properties.

(b) A test method shall give relevant and useful results. That means, that the exposure conditions in the test must simulate important and typical parameters of a real fire and, for instance, for the loading and restraint conditions, the decisive parameters of the fire behaviour of a real structure.

(c) A test method must give reliable and quantitative results with an acceptable degree of reproducibility among laboratories and repeatability within a laboratory.

(d) A test method must comprise a recording and reporting of data of measurements in such an extent, that different practical applications of the test results can be facilitated. That means, for instance, that the results of a fire test, made in one country, should be directly applicable as a basis for classification in different countries with varying classification requirements. This gives as a consequence, that a test method ordinarily ought to provide continuous scales of measure and that a test method should include a full description of the procedure of the test together with general test criteria, while detailed classification requirements are to be excluded [8]. It can be useful to supplement international fire test procedures with commentaries to serve as a guidance for planning, performance and reporting of a fire test and for an application of the test results to various situations in practice.

As concerns the existing ISO-recommendations for fire test procedures, it can be stated, that the test method for a determination of the calorific potential of building materials - ISO / R 1716 [9] - is giving values of the amount of heat released by a complete combustion, which now are generally applied in calculating the fire load of a compartment. Against the test method can be said, that the combustion conditions in the calorific potential test are more severe than in real fires. The importance of this difference can be illustrated fragmentarily by referring some test results, reported in [10], giving for a compact fire load component of paper a comparison of the calorific potential H according to ISO / R 1716 with the heat release H_f during a fire exposure, characterized in relation to the temperature- time curve of a standard fire resistance test. The results, summarized in the following table, are giving evidence of the great influence of the fire exposure conditions on the heat release for this type

Fire exposure	H_f/H
100 % ISO curve	0.73
67 % ISO curve	0 55
50 % ISO curve	0.27

of fire load. Further developments of laboratory test methods, recently published [11], [12], for a small scale determination of the rate of heat release of materials and linings at accurately specified heating conditions, relevant to real fires, could be a future way of solving this problem.

The non-combustibility test according to ISO Recommendation R 1182 [13] for a determination of whether a building material is non-combustible or combustible, is now frequently used for a classification in building code specifications. In spite of this fact, the test method does not fulfil the fundamental requirement (a) of giving precise information on one or several well-defined physical or chemical, material properties. A development, leading to a future replacement of the present non-combustibility test by either a number of single tests or an integrated test, connected to functionally based, distinct and well-defined material properties, therefore has a high degree of priority. About the same principal characterization is valid for that family of different national fire tests which is concerned with the contribution of materials, usually combustible linings on walls, to the initiation and spread of a fire.

The international research work in progress concerning the behaviour of building materials in connection with fire, has initiated a thinking in terms of "reaction to fire of materials" [14], [15]. In [14] then an integrated test method is presented, comprising the following relevant properties:

(a) the rate of heat release C,

(b) the inflammability I, which describes the ease with which an exothermic reaction occurs in the solid material (I_1) and in the gases set free by the material in the form of flaming (I_2),

(c) the flame propagation at the surface of the material P,

(d) the smoke opacity O, divided into the opacity when the material is in smouldering condition (O_s) and the opacity when the material is in flaming condition (O_f).

The different material properties are integrated into a reaction to fire index

$$I_{rf} = \frac{k_1C + k_2I_1 + k_3I_2 + k_4P + k_5O_s + k_6O_f}{k_1 + k_2 + k_3 + k_4 + k_5 + k_6}$$

where k_1 to k_6 are dimensionless coefficients of relative importance of the relevant properties.

In a long-term perspective, it is urgent to direct the research work towards a deduction of theoretical models which can describe, with acceptable degree of accuracy, different well-defined components of reaction to fire of building materials and/or the integrated concept as a whole. Such theoretical models then must take into account not only the relevant material properties but also the influence of varying environmental conditions, as concerns geometrical, thermal and ventilation characteristics.

The ISO Recommendation R 834 concerning fire resistance tests of elements of building construction fulfils the above requirement (a) in comprising a determination of the functionally based properties load-bearing capacity and fire separating capacity with respect to insulation and initial and ultimate integrity failure [16], [17]. As regards the requirements (b) and (c), the ISO recommendation comprises insufficiently accurate specifications in several respects, for instance concerning the heating and restraint characteristics, the environment of the furnace and the thermocouples for measuring the furnace temperature [17], [18]. From a basic functional point of view, it would be a fundamental improvement of the existing fire test procedure to replace the stipulation concerning a fixed temperature-time curve by a requirement, which specifies fixed realistic time curves representing the combustion energy supplied per unit time to the fire testing furnace [2], [3], [19], [20].

Going over from a conventional fire engineering design, based on classification systems, to a differentiated fire engineering design, the following summary statement can be made, as concerns a design of fire exposed, load-bearing structures or structural elements, cf. Figure 2.

A structural fire engineering design, directly based on differentiated gastemperature-time curves is characterized mainly by a theoretical design procedure. The applicability in practice of this procedure, essentially can be facilitated by design diagrams, calculated for different types of structures or structural elements by means of computers. The design procedure is not connected to any need of classifications and gives a low priority to the present standard fire resistance test of elements of building construction. In the design procedure, the results of such standard tests can be used either for a confirmation, point by point, of the theoretical treatment or for getting basic information, necessary for the calculations. In those cases, when the basic information depends on the detail characteristics of the process of fire development - for instance, basic data concerning the disintegration of structural materials, enlarged short-time effect of creep and shrinkage, effect of crack formation and spalling, behaviour and strength of fastening devices for different types of insulation, rate of increase in the depth of the charred layer at timber structures - the design procedure can necessitate experimental investigations at gastemperature-time curves diverging from the standard time-temperature curve. In most cases, the data required then can be determined by essentially less extensive experiments than the standard fire resistance test. The importance of internationally coordinated efforts for a development of such tests for essential material and component properties, connected to a differentiated fire engineering design, has been stressed at the "Colloque sur les Principes de la Sécurité au Feu des Structures", held in Paris 1971, and also within CIB Commission W14 [21] .

THE CONCEPT EQUIVALENT TIME OF FIRE DURATION

As emphasized above, a fundamental aim of a fire test is, that the test results can be used as data for a fire engineering design taking into account real conditions in practice. This very essential requirement of a fire test method will be discussed a little more in detail in the following, as concerns the possibilities of a translation for a load-bearing structure from a real fire exposure to the standardized heating conditions in fire resistance tests. Today, such a translation can be done over the concept equivalent time of fire duration.

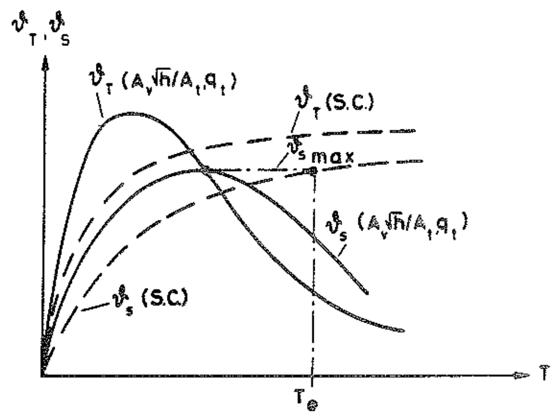

Figure 5. The concept equivalent time of fire duration T_e

In principle, the equivalent time of fire duration T_e can be defined according to Figure 5, giving an exemplification for a fire exposed uninsulated steel structure [3], [5], [18], [22]. The figure shows by the full-line curves the time-variation of the gastemperature ϑ_T and the steel temperature ϑ_s corresponding to a real fire action, determined by the fire load q_t, the opening factor $A_v\sqrt{h}/A_t$, and the thermal properties of the structures bounding the compartment. The dash-line curves give the standard time-temperature variation ϑ_T (S.C.) and the appurtenant time-curve of the temperature ϑ_s (S.C.) of the steel structure. A transfer of the maximum steel temperature $\vartheta_{s_{max}}$ for the real fire action to the curve ϑ_s (S.C.), belonging to the standard time-temperature curve, determines the equivalent time of fire duration T_e.

Defined in this way, the equivalent time of fire duration T_e will be a function of the basic influences on the process of fire development as well as structural parameters. This is fragmentary illustrated by Figure 6 [23], giving the equivalent time of fire duration T_e for insulated steel structures as a function of the fire load q_t and the structural parameter $U\lambda_i/dF$. The curves presuppose a fire compartment with an opening factor $A_v\sqrt{h}/A_t = 0.04\ m^{1/2}$ and with surrounding structures of a certain type. The dash-line curves of the figure are giving directly the level of the maximum steel temperature $\vartheta_{s_{max}}$.

A modified way of defining the equivalent time of fire duration T_e has been presented by Law [24], [25] with limited application to fire exposed insulated steel structures. Among elements of construction with varying thermal characteristics with respect to fire exposure that element is chosen, which for a given gastemperature-time curve of a real fire development gets a maximum steel temperature of a fixed value. T_e is then determined over the standard time-temperature curve for the same element and the same steel temperature. By repeating this procedure for different characteristics of real fires, a diagram can be constructed, applicable to a rough determination of the equivalent time of fire duration T_e for an insulated steel structure, irrespective of the detail properties of the structure.

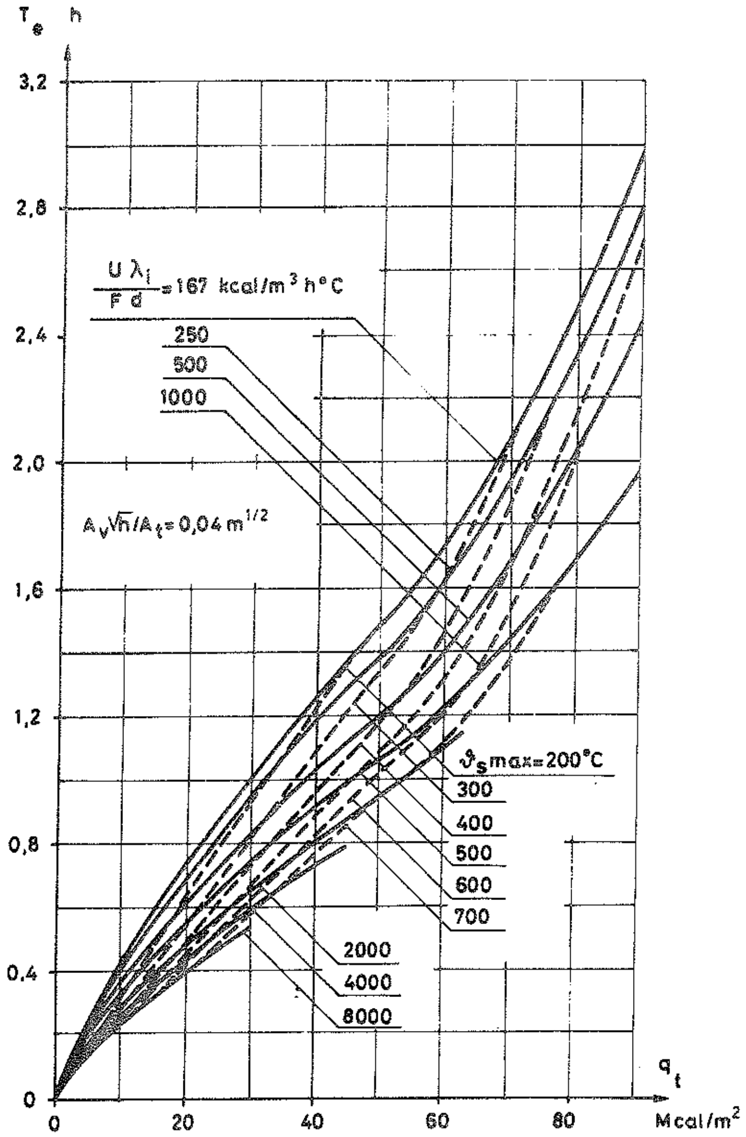

Figure 6. Equivalent time of fire duration T_e, defined according to Figure 5, for a fire exposed, insulated steel structure at varying fire load q_t and structural characteristics. Opening factor $A_v\sqrt{h}/A_t$ = 0.04 $m^{1/2}$. Dash-line curves give the corresponding maximum steel temperature $\vartheta_{s_{max}}$ [23]

A rough design diagram constructed in this way is exemplified in Figure 7 [23], giving a relation between the equivalent time of fire duration T_e and the parameter $B/\sqrt{A_v A_t \sqrt{h}}$. B then is the total fire load in Mcal of the compartment. The different curves of the figure refer to different values of the fire load q_t. The approximating straight line corresponds to the formula

$$T_e = 0.28 \frac{B}{\sqrt{A_v A_t \sqrt{h}}} \quad \text{(min)}$$

assuming A_v and A_t in m^2 and h in m.

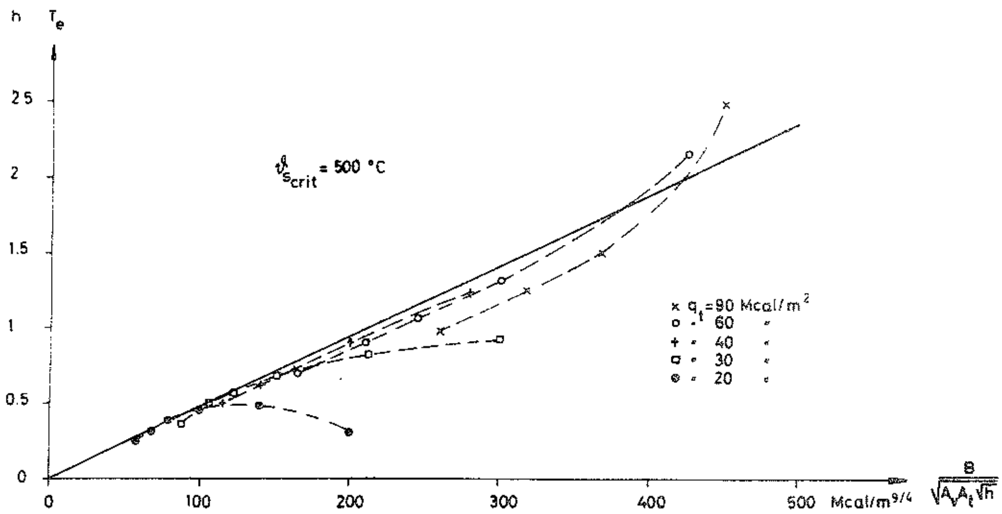

Figure 7. Equivalent time of fire duration for insulated steel structures T_e, determined in a more approximate way, as a function of the parameter $B/\sqrt{A_v A_t \sqrt{h}}$ [23]

The chosen fragmentary examples primarily serve in this connection to draw the attention to the possibilities of making test results, received at fixed standard conditions, generally applicable in a differentiated fire engineering design. A deduction of such means, connecting real fire conditions and exposure conditions in standardized fire tests, always ought to be an evident rule in relation to future developments of new and improved fire test procedures.

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