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Principles and rationale underlying calculation methods in relation to fire resistance of structural elements

Principes et analyse servant de base aux méthodes de calcul portant sur la résistance au feu des éléments structuraux

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 10158, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 92, *Fire tests on building materials, components and structures.*

Annex A of this Technical Report is for information only.

Introduction

This Technical Report was drawn up within ISO/TC 92/SC 2/WG 2 with the intention of providing a general background, with respect to the principles that should be followed as well as the rationale employed in the development of guidance documents on

— interpolation and extrapolation by analogy and calculation of results of fire resistance tests;

— analytical determination of fire resistance of structural elements.

The Working Group is now preparing such guidance documents, intended for issue as ISO Technical Reports. A parallel task of the Working Group is a survey on the need for tests for determination of data as input for analytical design of fire exposed structures and structural elements.

Role of ISO/TC 92

The role of ISO/TC 92 in the international development of analytical and computerized methods for structural fire design is defined by the terms of reference for SC 2/WG 2 which read

a) to develop documents which give guidance on how the results of ISO fire resistance tests of structures can be extended by interpolation and extrapolation and applied in practice;

b) to study the interrelation between experimental and analytical methods for the determination of fire resistance and to propose solutions to ensure consistency between the two;

c) to analyse the needs and suggest additional tests to provide data as input for analytical methods;

d) to keep its activities within the scope of SC 2.

The Working Group has identified a number of well-defined tasks from these terms of reference and is now preparing a series of basic documents which are intended for issue as ISO Technical Reports, as follows:

a) state of the art report and guidance document on interpolation and extrapolation by analogy and calculation of results of fire resistance tests for different types of load-bearing structural elements;

b) state of the art report and guidance document on analytical determination of fire resistance of load-bearing structural elements;

c) survey on the need for tests for determination of data as input for analytical design methods.

A simplified questionnaire has been circulated to all the member countries of ISO/TC 92/SC 2 concerning the interpolation and extrapolation of fire resistance test data and the analytical determination of the fire resistance of structural elements.

The response obtained from the questionnaire indicates that calculation procedures for the interpolation and extrapolation of fire resistance test data are accepted by authorities in several countries. The practices do, however, vary in regard to the limitations of the application of the procedure as far as variations in the tested prototypes are concerned.

The replies have also confirmed that there is no current basis available for assessing the influence of variations in the tested prototypes upon the performance of doors, windows, shutters, dampers and ducts, other than in regard to the size of the tested assembly.

There is also an indication of a somewhat more fragmentary basis for calculations involving non-load-bearing separating elements than for load-bearing structural elements such as floors, beams, columns and walls. There is also a variation in the character of the calculation procedures for interpolation and extrapolation which ranges from an approximate estimation to a thorough analysis.

The number of countries where the authorities accept a classification based upon an analytically determined fire resistance is somewhat more limited. However, in most countries where such classifications are not normally accepted, an analytical determination may be developed and accepted for a particular design.

In connection with the circulation of the questionnaire and later, references [1] to [29] (see annex A) were identified as useful bases for the analytical determination of the fire resistance of building elements and for analytical structural fire design.

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Principles and rationale underlying calculation methods in relation to fire resistance of structural elements

1 Scope

This Technical Report is intended to provide a background, with respect to the principles that should be followed as well as the rationale employed in the development of calculation methods for the determination of the fire resistance of elements of building construction.

Clause 3 contains explanations of some of the basic terms employed in the development and application of the concept of fire resistance, and proceeds to relate them first to the test method and then to the requirements that are typically considered in current documents which regulate building construction.

Clause 4 contains a discussion concerning the significance of fire resistance.

Clause 7 elaborates upon the development and application of calculation methods which are associated with the results obtained from fire resistance tests, and concludes with a review of the considerations involved in their continuing development and consolidation.

Clause 8 begins with a survey of the methods that are presently available for structural fire design, followed by an enumeration of the precepts that appear to be applicable to their use. The clause terminates with the listing of certain conclusions which appear to be appropriate at this time, as well as some actions which are indicated following this review.

Clause 9 deals in more detail with the considerations involved in the development and application of calculation methods which are directly related to an analytical determination of fire resistance.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this Technical Report. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Technical Report are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 834:1975, *Fire-resistance tests — Elements of building construction.*

ISO 3261:1975, *Fire tests — Vocabulary.*

3 Definitions

For the purposes of this Technical Report, the following definitions apply.

3.1 fire resistance: As presently defined in ISO 834, the term "fire resistance" means the duration of heating, expressed in units of time in accordance with the standard fire resistance test until failure occurs, under the conditions — load-bearing capacity, insulation, integrity — appropriate to the specimen. 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

$$T - T_0 = 345 \log_{10}(8t + 1) \qquad \ldots (1)$$

where

t is the time, in minutes;

T is the furnace temperature, in degrees Celsius, at time t;

T_0 is the furnace temperature, in degrees Celsius, at time $t = 0$.

NOTE 1 The fire resistance of tested elements of building construction is typically expressed by the number of minutes, hours, or fractions of hours during which the building element meets certain functional criteria with respect to load-bearing capacity for a load-bearing structural element, insulation and integrity for a separating element, and load-bearing capacity as well as insulation and integrity for a load-bearing and separating element.

For load-bearing structural elements, the test method requires that the specimen under test shall not collapse.

In practice, the ultimate load-bearing capacity of a structural element is established by either a critical value of deflection, a maximum rate of deflection, or a critical temperature, depending upon the circumstances.

For elements which have a separating function, the test method specifies that the average temperature of the unexposed face of the specimen under test shall not increase above the initial temperature by more than 140 °C. It is also required that the maximum temperature at any point on this face shall not exceed the initial temperature by more than 180 °C and at the same time shall not exceed 220 °C irrespective of initial temperature.[1)].

With respect to integrity, the specimen under test is said to have failed when flames or hot gases can pass through cracks, holes or other openings which may be present initially or are formed during the test. Integrity failure is deemed to have occurred if a specified cotton pad is ignited, when it is applied to the opening.

Other terms which may be used in this Technical Report and which are otherwise not yet included in ISO vocabulary documents such as ISO 3261 are defined as follows:

3.2 fire compartment: An enclosed space in a building that is separated from all other parts of the building by an enclosing construction having a specified period of fire resistance, within which a fire can be contained, without spreading to another part of the building. The construction enclosing the fire compartment can contain portions (e.g. windows and doors) necessary for its function, which have a fire resistance lower than this specified period. A fire compartment can be divided into subcompartments. It may also extend through one or more floors, in which event it becomes a multi-level or multi-storey fire compartment.

3.3 real fire: A fire which develops in a building and which is influenced by such factors as the type of building and its occupancy; the combustible content (the fire load); the ventilation, geometry and thermal properties of the fire compartment; the extinguishing systems in the building and the actions of the fire brigade. Real fires are complex phenomena. Consequently, in a structural fire design, idealized versions of real fires are employed.

3.4 experimental fire: A full or reduced scale fire with specified and controlled characteristics.

3.5 design fire: A fire with specified exposure data intended for use in connection with structural fire design calculations.

A design fire may either be representative of the thermal exposure described by the standard time-temperature curve in accordance with the ISO 834 [equation (1)], or some non-standard exposure intended to simulate particular fire exposure conditions.

4 Associated criteria

The basic element currently employed in the determination of fire resistance is the standard fire resistance test in accordance with ISO 834, or one of the various national equivalents. The tested element of building construction is typically required to be representative of the actual building construction for which the information on fire resistance is required, with respect to materials, form and design, as well as having prescribed minimum dimensions.

On this point there is currently a divergence of opinion among experts in several countries in regard to the utilization and acceptance of data derived from tested assemblies. Most authorities accept the analogous concept of the applicability of fire resistance derived from a test to building construction of a generally larger scale. There is also an increasing acceptance of the application of test results together with engineering studies to determine the acceptance of alternative components and materials to those qualified in tested assemblies. These considerations, together with the use of interpolation and extrapolation in the expansion of the applicability of the test data are further discussed in clause 7.

As noted in the introductory remarks, a current survey indicates that fire resistance derived from calculations involving the consideration of the basic properties of materials at the elevated temperatures, anticipated under fire exposure conditions, has thus far achieved limited acceptance among authorities. However, the current trend is that calculation methods as an alternative to testing will become accepted by authorities in more and more countries. The European recommendations and the related manual for the design of steel structures exposed to standard fire conditions recently drawn up by the European Convention for Constructional Steelwork (ECCS) [23], [26], together with the corresponding design guide for fire exposed concrete structures prepared under the auspices of the Comité euro-international du béton (CEB) [20], [29], will further stimulate such acceptance.

1) In the revision of ISO 834:1975, the criterion to limit the temperature to 220 °C has been deleted.

5 Application of fire resistance

The requirement of fire resistance in building codes, regulations, etc., is a means of preventing the spread of fire by dividing a building into fire compartments by fire separations having an appropriate degree of fire resistance, or preventing the failure of load-bearing structures or structural elements.

The level of fire resistance required is influenced by such factors as the building height and volume, the type of occupancy, and the importance of the structure or structural element to the overall stability of the building. It is also influenced by the fire load, which determines the severity of the fire exposure. This was first quantified by Ingberg who derived the relationship

$$t_d = f(Q/A_f) = f(q_f) \qquad \ldots (2)$$

where

t_d is the standard fire duration;

Q is the fire load in the compartment;

A_f is the floor area of the fire compartment;

q_f is the corresponding fire load density.

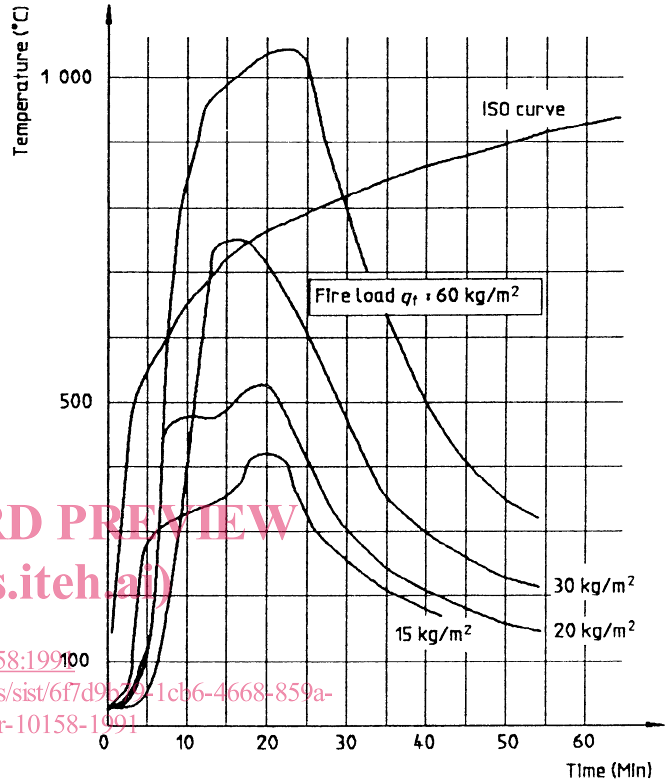
This relationship is still the basis of most current codes and regulations. In more recent relationships, the additional importance of the ventilation, the geometry and the materials of the fire compartment boundaries have also been considered [see equation (3)].

6 Significance of fire resistance

The fire resistance test method prescribes a standard fire test environment which is characterized by the "standard temperature-time curve" expressed mathematically by equation (1).

The time curve of the furnace temperature, T, is shown in figure 1 for T_0 = 20 °C. For comparison, figure 1 also includes curves illustrating the average gas temperatures obtained inside a fire compartment during four full-scale tests in which different fire load densities (q_f) were employed under specified ventilation and thermal characteristics of the compartment [30]. The curves demonstrate that the heat exposure in a real (experimental) fire can deviate consideraby from the heat exposure prescribed by the standard fire resistance test.

The purpose of the standard fire environment represented by the standard temperature-time curve is to provide test conditions reasonably representative of a severe fire exposure condition for comparing the performance of various representative forms of building construction. It is, however, important to note that this standard fire exposure condition does not necessarily represent an actual fire exposure situation, nor are the test results necessarily indicative of the behaviour of building elements under real fire exposure conditions. The test does, nevertheless, grade the performance of load-bearing and/or separating building elements on a common basis.



NOTE – The compartment used for the test had a floor area of about 12 m² and a volume of about 40 m³ [30].

Figure 1 — Comparison of ISO temperature-time curve with temperature-time curves obtained from compartment fires with fire load densities of 15 kg, 20 kg, 30 kg and 60 kg wood per square metre of floor area

7 Extension of data from fire resistance tests

7.1 General

The calculation methods which are most likely to achieve initial acceptance by designers and authorities are those which extend the data obtained from standard fire resistance tests conducted upon representative forms of building structure and which relate to the conditions, performance requirements, and acceptance criteria presently prescribed by the test method. This clause deals with the rationale and principles associated with such methods.

7.2 Generally accepted precepts involving the extension of test data

7.2.1 The most simplistic application of the test data derived from a standard fire test is to duplicate, completely, the sub-assembly of the building structure that is to be the subject of a fire design.

7.2.2 It is, however, necessary to make a number of compromises in the representation of the actual building construction, beginning in most cases with the fact that the tested construction is invariably of a smaller scale than the construction it is intended to represent.

7.2.3 A generally accepted precept among authorities is that the fire resistance achieved by the application of the test method to a model representative of an actual full scale structure is appropriate for use in such building structures employing components with larger spans and hence having greater size (mass per metre, cross-sectional area, or section modulus) than those employed in the tested prototype. Such acceptance is predicated upon the fact that the structural components concerned have been appropriately loaded during the fire resistance test to develop their full theoretical design stresses.

7.2.4 An accommodation of the fire design requirements of a wide variety of building constructions by the correspondingly limited number of fire resistance tests that can be conducted has seen the gradual emergence and acceptance of a number of practices, the acceptance of which is based upon what might be termed "an analogous worst case proposition". As an example, it has been found that load-bearing elements such as beams, girders and joists yield higher fire resistance when subjected to fire resistance tests as part of floor, or roof and ceiling assemblies, than they would when tested separately. Some authorities have consequently accepted the premise that the structural members in tested assemblies may be replaced by other load-bearing elements which, when tested separately yield fire resistances not less than that of the assembly into which they will be substituted in order that the qualifying assembly may be more representative of the actual building structure under consideration.

7.2.5 The matter of the substitution of structural members from one type of fire tested structure to another, when selecting a tested assembly which represents as closely as possible a particular form of building structure, is regulated by some authorities in accordance with the following precepts:

a) the capacity for heat dissipation from the structural member in the assembly where a structural member is being substituted shall be equal to or greater than that of the assembly in which it was originally subjected to fire test;

b) the capacity for heat transfer to the structural member in the assembly in which a structural member is being substituted shall be equal to or less than that in the assembly in which it was originally tested;

c) the load deformation characteristics of the assembly in which the structural member is being substituted shall be equal to or lower than those of the assembly in which it was originally tested.

It should be noted that the first precept referred to above would preclude the substitution of structural members tested as a part of a steel deck/concrete floor assembly to an assembly comprising an insulated steel roof assembly.

Similarly, the second precept precludes the replacement of structural members comprising wide flange, rolled steel structural shapes with members comprising fabricated open-web type steel joists. However, a larger rolled steel structural shape is always permitted to replace a smaller one.

In addition, the authorities in some countries, recognizing the difference in performance between those structural members which have been restrained against thermal expansion during a fire test and those which have not, and attempting to relate such information to the anticipated performance of actual building construction under varying conditions of thermal restraint, have imposed the following additional criteria in regard to the substitution of structural members:

d) the fire resistance of the unrestrained structural member which is substituted shall be equal to or greater than that of the structural member being replaced;

e) the fire resistance of the restrained structural member being substituted or of the assembly in which the member was tested shall be equal to or greater than that of the assembly into which the member is being substituted.

7.2.6 The fire resistance of an unrestrained flexural member (beams, floors, roofs) is generally less than the fire resistance of that same member when it is subjected to restraint. Members which have been tested with unrestrained end conditions may, therefore, be appropriately substituted in fire tested constructions of actual building constructions which will be subjected to restraint in practice. The reverse of this procedure is not, however, appropriate.

7.2.7 The fire resistance of a restrained flexural member may be less than the fire resistance of an unrestrained flexural member in the case where the longitudinal load, caused by the restraint, is applied above the cross-sectional axis of gravity, resulting in an increase of the load-depending bending caused by the heating in fire.

7.2.8 Another consideration in connection with the substitution of structural components is the effect of substituting composite structural members for non-composite structural members, and vice versa. It is generally accepted, for example, that structural elements which have been subjected to fire tests with steel floor units designed for composite action, and loaded so as to develop the full theoretical stresses contemplated by the design, have been qualified for their use in the building construction that is being represented, of either composite or non-composite floor units. On the other hand, it is cautioned that the level of fire resistance may not be maintained if composite units are employed in the building construction which is intended to duplicate the details of an assembly which has been accorded a level of fire resistance on the basis of its performance when tested with non-composite units.

7.2.9 Of additional structural consideration in connection with the analogous extension of fire test data is the treatment of requirements for concrete strength, thickness and type. Some authorities may permit the compressive strength of concrete to be reduced by a specified amount when comparing the strength of the concrete in the tested structural element to the design requirement in the actual structure to be represented. On the other hand there is no limit upon the maximum strength of the concrete in the actual structure represented by the tested prototype. From a structural standpoint, there is no limitation upon the concrete thickness, but there is no provision for the unrestricted exchange of low density and normal density concrete.

7.2.10 The extension of test data by analogous interpretation may also be applied in regard to the fire resistance with respect to insulation of tested assemblies in a more specific sense. For example, it is a generally accepted principle, in the case of floor and roof assemblies employing a suspended, protective membrane ceiling below the structural members, that the depth of the plenum space between the underside of the floor and the top of the protective ceiling may be increased to accommodate the deeper structural members without detracting from the performance established from the data related to the tested prototype.

7.2.11 It is also generally accepted that increasing the thickness of the concrete topping on a floor and ceiling assembly will have a beneficial effect on the fire resistance with respect to insulation and, to a less specific degree, on the structural performance of the tested assembly under fire exposure conditions.

7.2.12 While it is recognized that increasing the thickness or number of layers of insulation and the provision of air gaps will generally add to the thermal resistance of a tested assembly, it is not always possible to apply this in an analogous sense because of the effects of the increased insulation in some circumstances upon the performance of the structural members. It is, therefore, usually necessary to resort to further full or small-scale testing, supplemented by calculations, in assessing the performance of such assemblies.

7.2.13 In certain cases, an additional or otherwise improved insulation can give rise to a decrease in the fire resistance of a structural assembly. This will be the case if a slab of ordinary concrete is replaced by a slab of aerated concrete in a roof or floor assembly, composed of a top slab, load-bearing steel beams, and a suspended ceiling. Improving the insulation of the slab then causes an increased rate of heating of the load-bearing beams. For a fire exposed concrete structure, a supplementary insulation on the unexposed side of the structure can increase the risk of spalling.

In conclusion, it should be noted that analogous interpretations of data with respect to fire resistance tests of building structural elements, are invariably expressed in qualitative rather than quantitative terms.

7.3 Principles currently followed in considering specific variations from tested assemblies

The following principles are those currently observed when considering variations that are more specific than the generalizations which have thus far been discussed. They are employed in the development of periods of assigned fire resistance which customarily evolve from engineering studies conducted upon a tested assembly or a series of tested assemblies, and involve the application of reasoned analogy, calculations, and the conduct of small- and large-scale tests in the extension of test data.

7.4 Variations of insulation

7.4.1 The essential characteristics of insulating materials that need to be considered in extending the data from a tested specimen relate to their thermal and mechanical behaviour under fire exposure conditions.