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Fire resistance — Guidelines for evaluating the predictive capability of calculation models for structural fire behaviour

Résistance au feu — Lignes directrices pour évaluer l'aptitude des modèles mathématiques à simuler le comportement des feux de structures

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, 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), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 15656 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 2, *Fire containment*.

ISO/TR 15656 is one of a series of documents developed by ISO/TC 92/SC 2 that provide guidance on important aspects of calculation methods for fire resistance of structures:

— ISO/TR 15655, *Fire resistance — Tests for thermo-physical and mechanical properties of structural materials at elevated temperatures for fire engineering design*

Others documents in this series are currently in preparation and include:

— ISO/TS 15657, *Fire resistance — Guidelines on computational structural fire design*

— ISO/TS 15658, *Fire resistance — Guidelines for full scale structural fire tests*

Other related documents developed by ISO/TC 92/SC 2 that also provide data and information for the determination of fire resistance include:

— ISO 834 (all parts), *Fire-resistance tests — Elements of building construction*

— ISO/TR 10158, *Principles and rationale underlying calculation methods in relation to fire resistance of structural elements*

— ISO/TR 12470, *Fire-resistance tests — Guidance on the application and extension of results*

— ISO/TR 12471[1)], *Computational structural fire design — State of the art and the need for further development of calculation models and for fire tests for determination of input material data required*

1) In preparation.

Introduction

Structural fire behaviour for a standard fire exposure has traditionally been experimentally determined by test methods described by International Standards such as ISO 834 (all parts). For a variety of reasons, calculation methods have been developed as alternative methodologies for determining the fire endurance or fire resistance of structural members or assemblies. Since fire resistance is a critical component of fire safety regulations, it is essential that objective assessments of the accuracy and applicability of such calculation methods be conducted. In a review of the state of the art of computational structural fire design, ISO/TR 12471, it was noted the “rapid progress in analytical and computer modelling of phenomena and processes of importance for a fire engineering design stresses the need for internationally standardized procedures for evaluating the predictive capabilities of the models and for documenting the computer software.” The development of this Technical Report is toward that end.

Fire resistance — Guidelines for evaluating the predictive capability of calculation models for structural fire behaviour

1 Scope

This Technical Report provides guidance for evaluating the predictive capability of calculation models for structural fire behaviour. It is specific to models that are intended to predict the fire resistance or fire endurance of structural members or assemblies. Such models include models simulating the thermal behaviour and mechanical behaviour of fire-exposed load-bearing and/or separating structures and structural elements.

In this Technical Report, the term “model” includes all calculation procedures that are based on physical models. These mechanistic-based or physical models encompass all the physical, mathematical and numerical assumptions and approximations that are employed to describe the behaviour of structural members and assemblies when subjected to a fire. In general, such physical models are implemented as a computer code on a digital computer. The application and extension of results from calculation methods are generally limited to performance resulting from standard tests. Aspects of this Technical Report are applicable to calculation procedures not based on physical models. Mechanistic-based models can often be used to calculate the behaviour of structures in non-standard fire exposures.

The process of model evaluation is critical in establishing both the acceptable uses and limitations of fire models. It is not possible to evaluate a model in total; instead, this Technical Report is intended to provide methodologies for evaluating the predictive capabilities for specific uses. Documentation of suitability for certain applications or scenarios does not imply validation for other scenarios.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13943:2000, *Fire safety — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 apply.

NOTE In discussions of models, the terms “evaluation”, “verification” and “validation” have taken on specific but different meanings. There is no consensus on the requirements for an evaluation to be considered verification or validation. The dictionary definition of “evaluate” is “to examine and judge.” “Verify” is defined as “to establish the truth, accuracy, or reality of.” The definition of “validation” includes “the process of determining the degree of validity of a measuring device.” “Valid” is considered to “imply being supported by objective truth or generally accepted authority.” For the purposes of this Technical Report, no judgement is made as to what is required for a model to be “verified” or “validated.” The intent is to review methodologies that are available to evaluate fire models for purposes of gaining verification or validation of such fire models for their defined applications. The term “evaluation” is used in all cases. “For clarity it would be better for the word (i.e. validation) not to be used at all but for people to say explicitly what they mean.”[1]

4 Background information

4.1 General

Structural fire behaviour for a standard fire exposure has traditionally been experimentally determined by test methods described by standards such as ISO 834. For a variety of reasons, calculation methods have been developed as alternative methodologies for determining the fire endurance or fire resistance of structural members or assemblies. Since fire resistance is a critical component of fire safety regulations, it is essential that objective assessments of the accuracy and applicability of such calculation methods be conducted. In a review of the state of the art of computational structural fire design (ISO/TR 12471), it was noted that “rapid progress in analytical and computer modelling of phenomena and processes of importance for a fire engineering design stresses the need of internationally standardized procedures for evaluating the predictive capabilities of the models and for documenting the computer software.” In an earlier review of fire-dedicated thermal and structural computer programs, it was noted that programs are commonly only validated against specific and limited test data. Little work had been presented by way of general validation of these methods.

ASTM has developed ASTM E 1355, *Standard guide for evaluating the predictive capability of fire models*. This was used to develop the initial draft of this document. ISO/TC 92/SC 4 is developing guidelines, ISO/TR 13389, *Fire engineering — Assessment and verification of mathematical fire models*. These documents provide guidance that are applicable to any fire model but their primary intended applications are to models that predict fire growth in compartments. A number of papers have been published on the evaluation of a fire model[2-10]. Some of these documents will be reviewed in ISO/TR 13389. A 1993 review of seven thermal analysis programs and fourteen structural analysis was dedicated to fire endurance analysis[2].

An assessment of fire models based on a matrix of criteria and weighting factors has been presented[10]. Criteria include field of application (4 points), scientific verification (6 points), precision of method (2 points), physical background (1 point), completeness (2 points), input existent (2 points), user friendliness (1 point) and approval/standard or experience (2 points). The sum of the weighting factors is 20 points. The system was applied to existing simplified methods for concrete, structural steel and timber.

4.2 Potential users and their needs

This Technical Report is intended to meet the needs of users of fire models. Users of models need to assure themselves that they are using an appropriate model for an application and that it provides adequate accuracy. Developers of performance-based code provisions and other approving officials need to ensure that the results of calculations using mathematical models show clearly that the model is used within its applicable limits and has an acceptable level of accuracy. The methodologies discussed in this Technical Report will assist model developers and marketers in developing the documentation of predictive capabilities for specific applications that should be available on their calculation methods. Part of model development includes the identification and documentation of precision and limits of applicability, and independent testing. Educators can use the methods to demonstrate the application and acceptability of calculation methods being taught. This Technical Report should also be useful for educators of future model developers so future models of greater complexity and availability are used within their limitations of application and precision.

4.3 Predictive model capabilities, uncertainties of design component (from ISO/TR 12471)

Few systematic studies of the predictive capabilities of models and related computer software, used for describing the simulated fire exposure and the thermal and mechanical behaviour of fire exposed structures, have appeared in the literature. Recent studies seem to indicate that the situation now is improved. Such studies include compartment fire modelling[1,11,12] and modelling of the thermal and mechanical behaviour of structures[2,13]. General categories have been identified regarding possible sources of error in using a computer model to predict the value of a state-variable such as temperature or heat flux[1,11]. The categories specified are

a) unreality of the theoretical and numerical assumptions in the model,

b) errors in the numerical solution techniques,

c) software errors,

d) hardware faults, and

e) application errors.

For 10 zone models and 3 field models for the compartment fire, the Loss Prevention Council provides the following information: degree of validation, limitations, and restrictions on compartment size, number of vents and number of fuels that can be accommodated, and number of organizations using the model[12]. Useful conclusions are drawn with respect to input/output data, experience of using the models, model validation, and potential limitations. A survey[2] discusses the theoretical background to 7 thermal and 14 structural behaviour, fire-dedicated, computer programs, together with their strengths and weaknesses. The differences between the programs were found to lie mainly in the material models adopted, the material data input, the user-friendliness and documentation of the software. The majority of the available fire-dedicated structural programs still require significant development and, as most of them are not user-friendly or properly documented, using them effectively and universally would be very difficult.

Applied to fire exposed steel columns, comparative calculations are reported[1] of the structural behaviour by five computer programs. In terms of the ultimate resistance of the columns, the calculated results are very similar, with a maximum difference between two programs of 6 %. Greater differences are observed for the displacements of the columns, probably mainly due to different ways of considering the residual stresses at increasing temperature in the program. When evaluating the results, it is important to note that the same mechanical behaviour model for steel at transient elevated temperatures (the one in ENV 1993-1-2, *Eurocode 3 — Design of steel structures — Part 1-2: General rules —– Structural fire design*) was used in all computer programs.

For sensitivity and uncertainty studies of relevance for structural fire design, there are very few reported in the literature. The most comprehensive studies are probably still those presented by 20 years ago[14-16]. The methodology developed for these studies is quite general and applicable to a wide class of structures and structural elements. To obtain applicable and efficient final safety measures, the probabilistic analysis is numerically exemplified for an insulated, simply supported steel beam of I-cross section as a part of a floor or roof assembly. The chosen statistics of dead and live load and fire load are representative for office buildings.

With the basic data variable selected, the different uncertainty sources in the design procedure were identified and dissembled in such a way that available information from laboratory tests could be utilized in a manner as profitable as possible. The derivation of the total or system variance var(R) in the load bearing capacity R was divided into two main stages: variability var($T_{\max}$) in maximal steel temperature $T_{\max}$ for a given type of structure and a given design fire compartment, and variability in strength theory and material properties for known value of $T_{\max}$.

The results obtained are the decomposition of the total variance in maximum steel temperature $T_{\max}$ into the component variances as a function of the insulation parameter $\kappa_n = A_i\, k_i\, /(V_s d_i)$ (see Figure 1), where A_i is the interior surface area of the insulation per unit length, d_i the thickness of the insulation, k_i the thermal conductivity of the insulating material corresponding to an average value for the whole process to fire exposure, and V_i the volume of the steel structure per unit length. Increasing κ_n expresses a decreased insulation capacity.

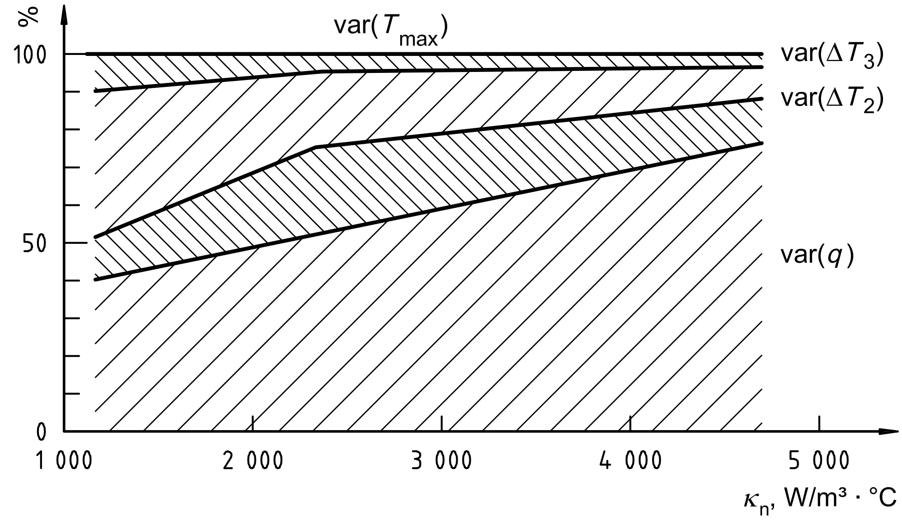


Figure 1 — Separation of total variance in maximum steel temperature T_{max} into component variance as a function of insulation parameter κ_n

The component variances refer to the stochastic character of the fire load density q, the uncertainty in the insulation properties κ, the uncertainty reflecting the prediction error in the theory of compartment fires and heat transfer from the fire process to the structural member ΔT_2, and a correction term reflecting the difference between a natural fire in a laboratory and under real life service conditions ΔT_3 . Analogically, there is the decomposition of the total variance in the load bearing capacity R into component variances as a function of the insulation parameter κ_n (see Figure 2). The component variances refer to the variability in the maximum steel temperature T_{max} variability in material strength M, the uncertainty reflecting the prediction error in the strength theory $\Delta\Phi_1$, and the uncertainty due to the difference between laboratory tests and *in situ* fire exposure $\Delta\Phi_2$.

Uncertainty studies of fire-exposed concrete structures are scarce. A report[17] breaks the total variance in fire resistance or load-bearing capacity into component variances as a function of the slenderness ratio λ for an eccentrically compressed, reinforced concrete column (see Figure 3). The component variances are related to the following stochastic variables: f_c is the compressive strength of concrete at ordinary room temperature, f_s is the strength of reinforcement at ordinary room temperature, b is the width of the cross section, h is the height of the cross section, x_t is the position of tensile reinforcement, x_c is the position of compressive reinforcement, $f_{S,T}$ is the yield stress of steel as a function of temperature T, and k_c is the thermal conductivity of concrete.

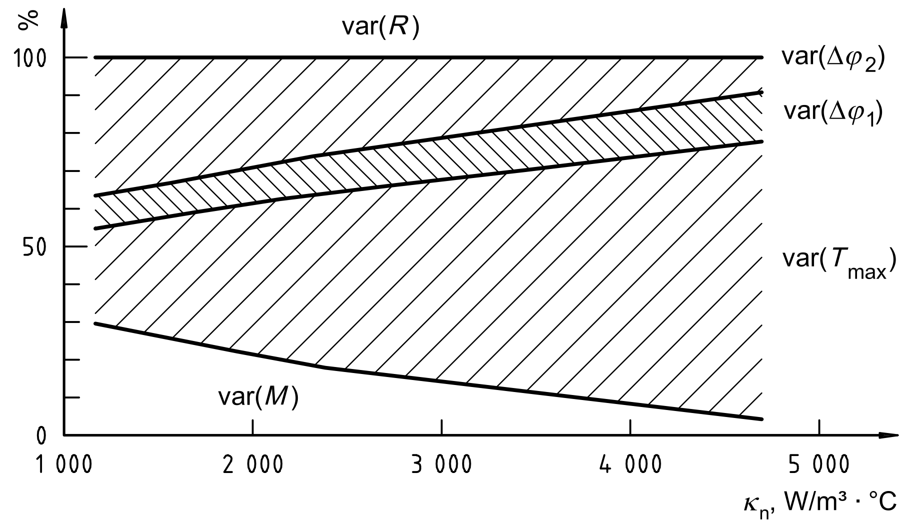
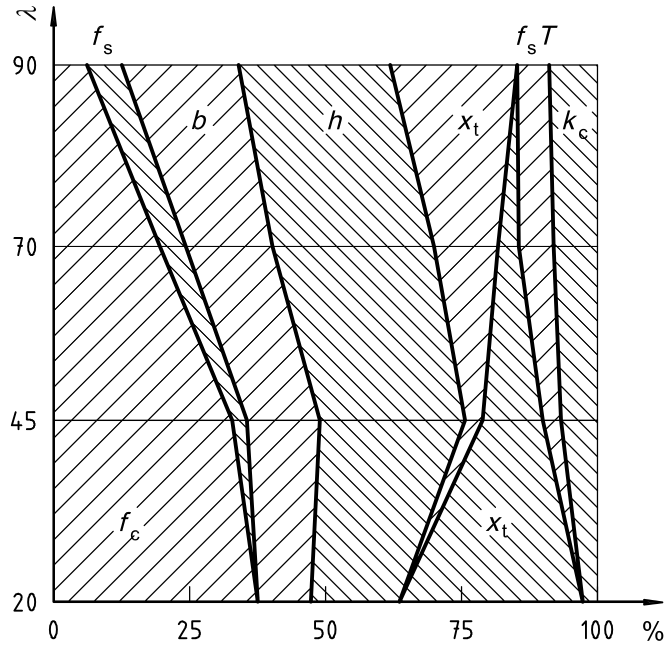


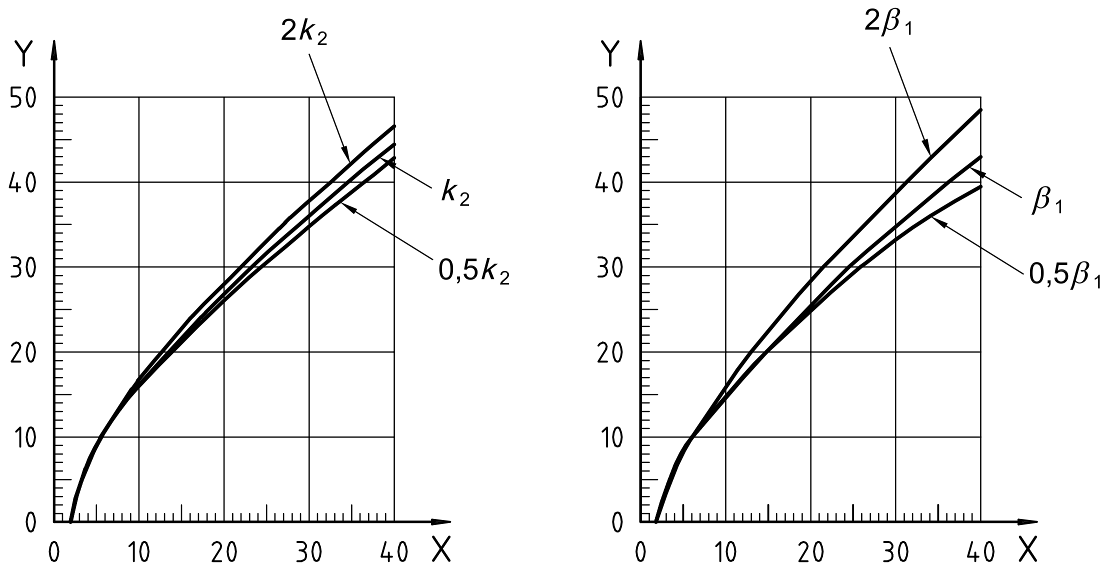
Figure 2 — Separation of total variance in load bearing capacity R into component variances as a function of insulation parameter κ_n



NOTE Concrete B25, percentage of reinforcement μ = 0,2 %, b = h = 30 cm, eccentricity e = 0,2 h.

Figure 3 — Separation of total variance in resistance or load-bearing capacity R into component variances as a function of slenderness ratio λ for an eccentrically compressed, reinforced concrete column

Results of sensitivity studies regarding a fire engineering design of timber structures have been reported[18]. The study reports deals with the sensitivity of the charcoal layer penetration for a fire-exposed timber structure as a function of certain material input in a defined simulation model, including the influence of varying the thermal conductivity of the charcoal and the rate of surface reaction (see Figure 4). Another study[19] presented a first-order reliability analysis (FORM) of fire-exposed wood joist assemblies. By using non-linear least-square regression analysis on 42 full-scale tests, a time-to-failure model is developed, predicting the deterministic value of the resistance of the assembly. The exposure parameter is defined as the duration of the ventilation controlled compartment fire predicted by the fire load, and the window area and height, assuming constant rate of burning. Expressions describing the total system and component variances are developed which, when quantified, lead to a determination of the safety index β.



Key

X time, in minutes

Y depth, in millimetres

Figure 4 — Depth of charring as a function of time for variable thermal conductivity k_2 of charcoal and variable rate of surface reaction β_1

5 Outline of methodology

In this Technical Report, the evaluation of fire models is broken into seven primary components:

a) identification or definition of the model and scenario being evaluated;

b) evaluation of the application and use of the model when applied to a specific use;

c) identification of sources of errors in the predictions;

d) evaluation of the appropriateness of the theoretical basis and assumptions used in the model when applied to the entire class of problems addressed by the model;

e) evaluation of the mathematical and numerical robustness of the model and the accuracy of the computer code;

f) evaluation of the uncertainty and accuracy of the model results in predicting of the course of events;

g) evaluation of the model sensitivity to parameters.

Sufficient documentation of calculation models, including computer software, is absolutely necessary to assess the adequacy of the scientific and technical basis of the models, and the accuracy of computational procedures. Also, adequate documentation will help prevent the unintentional misuse of fire models. Scenario documentation provides a complete description of the scenarios or phenomena of interest in the evaluation to facilitate appropriate application of the model, to aid in developing realistic inputs for the model, and criteria for judging the results of the evaluation.

A model should be assessed for a specific use in terms of its quantitative ability to predict outcomes. Even deterministic models rely on inputs often based on experimental measurements, empirical correlations, or estimates made by engineering judgements. Uncertainties in the model inputs can lead to corresponding uncertainties in the model outputs. Sensitivity analysis is used to quantify these uncertainties in the model outputs based upon known or estimated uncertainties in model inputs.

