TECHNICAL REPORT

ISO/TR 15656

First edition
2003-12-01

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

Reference number
ISO/TR 15656:2003(E)

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Published in Switzerland

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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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.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.

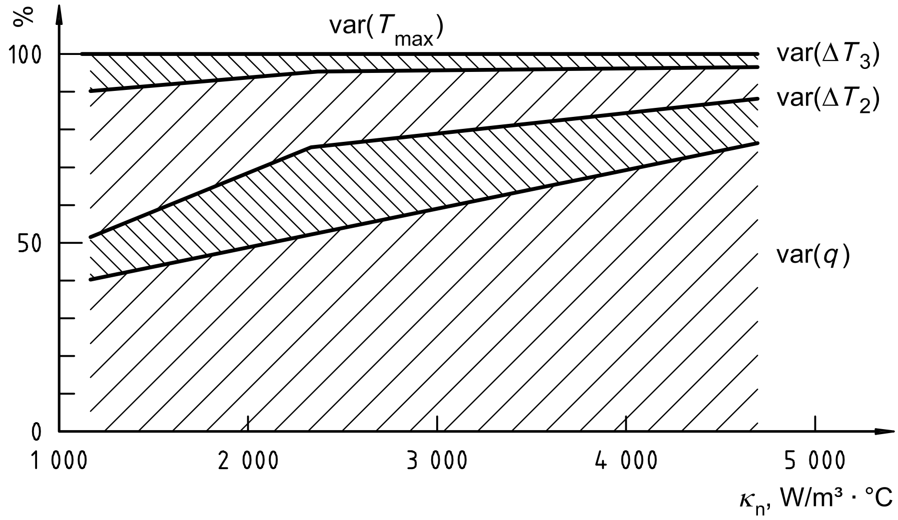


Figure 1 — Separation of total variance in maximum steel temperature T_{max} into component variance as a function of insulation parameter κ_n

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.

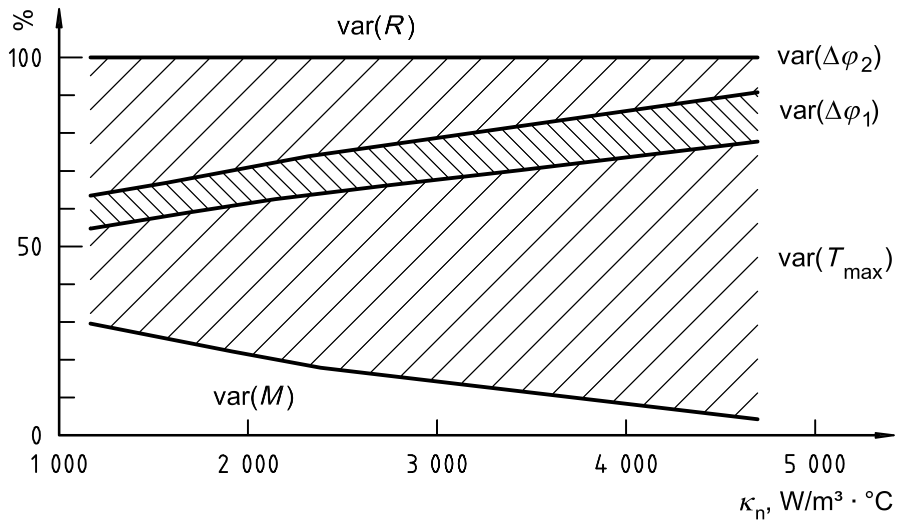
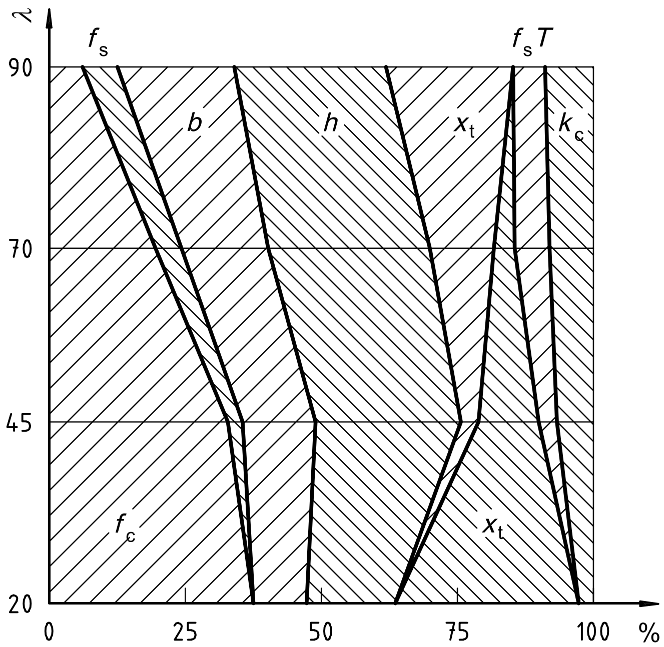


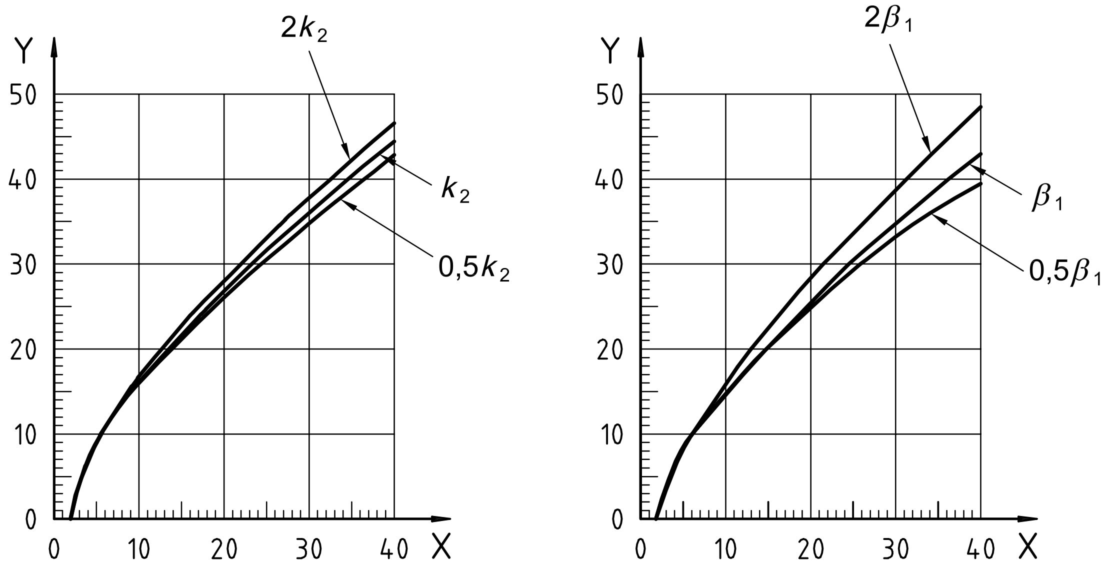
Figure 2 — Separation of total variance in load bearing capacity R into component variances as a function of insulation parameter κ_n



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.

In general, the results of measurement are only the result of an approximation or estimate of the specific quantity subject to measurement, and thus the result is complete only when accompanied by a quantitative statement of uncertainty. Guidance for determining the uncertainty in measurement is provided in the *Guide to the Expression of Uncertainty in Measurement*.

The computer implementation of the model should be checked to ensure such implementation matches the stated documentation. An independent review of the underlying physics and chemistry inherent in a model ensures appropriate application of sub-models that have been combined to produce the overall model.

Information on methodologies discussed in this Technical Report can also be found in ISO/TR 13387-3:1999, *Fire safety engineering — Part 3: Assessment and verification of mathatical fire models*, and ASTM E 1355. These two documents are the primary documents used to prepare this Technical Report. ASTM E 1895, *Standard guide for determining uses and limitations of deterministic fire models*, provides an overall methodology for the systematic evaluation of fire models by model users, model developers and authorities having jurisdiction. While the scopes of these documents were all deterministic fire models, they tend to reflect an emphasis on models for the compartment fire itself. Emphasis in this Technical Report is on models for predicting structural fire behaviour.

6 Definition and documentation of model and scenario

6.1 Types of models

Fire models for structures normally consist of a heat-transfer model that provides the thermal profile input needed for the mechanical model and the mechanical model itself. Models available at present for structural fire engineering design have been systematically characterized with reference to a matrix of models for structure versus models for thermal exposure[20,21]. In the matrix (shown in Figure 5), there are two types of thermal models:

— H_1: the thermal exposure is the standard fire resistance test with the nominal temperature-time curve;

— H_2: the thermal exposure is that resulting from a real fire.

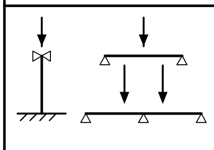
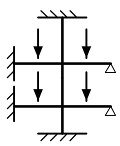
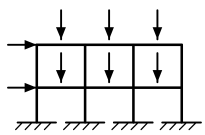
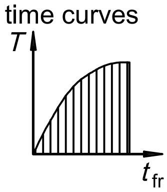
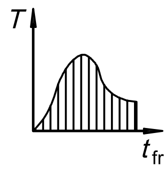
Model for thermal exposure		**Model for structure**		
		S_1	S_2	S_3
		Element	Substructure	Complete structure
				
H_1	Nominal temperature-time curves 	test or calculation (deterministic)	calculation exceptionally testing (deterministic)	
H_2	Real fire 	calculation (probabilistic)	calculation (probabilistic)	calculation (probabilistic) in special cases and for research

Figure 5 — Matrix of thermal exposure and structural behaviour models

Thermal exposure of a simulated real fire includes those computed by solving the energy and mass balance equations of the compartment fire or that determined from some systematized design basis. Such systemized design basis include the parametric fire of ENV 1991-2-2, *Eurocode 1 — Basis of design and actions on structures — Part 2-2: Actions on structures exposed to fire*, or sets of gas temperature-time curves.

The matrix provides for three types of structural behaviour models. These three types of models include:

— S_1: the analysis is for single structural elements;

— S_2: the analysis is for a substructure;

— S_3: the analysis is for the complete load bearing structure of the building.

A substructure model describes the mechanical behaviour of a part of the complete load-bearing system of a building with simplified boundary conditions at its outer ends or edges.

Models can be characterized in terms of the failure criteria. Failure criteria include

a) integrity criterion: passage of flames or hot gases;

b) thermal insulation criterion: excessive heat transmission, temperature rise;

c) load capacity criterion: load or deformation failure.

A failure of a structure in a fire is its loss of integrity. Models of integrity could depend on input from either the heat transfer model (thermal expansion) or the mechanical model (deflection).

Models can be characterized in terms of their outputs. These outputs include the following:

a) heat transfer/thermal profile;

b) mechanical/deflection;

c) mechanical/loss of load capacity;

d) integrity: delamination, spalling, dilation.

The model can be described in the context of the overall objectives of fire safety design.

EXAMPLE Structural response (from ISO 13392).

a) Global information

1) Prescribed/estimated parameters

— building, occupants, fire loads, fire scenarios environment

2) Intervention effects

— alarm, control + suppression activation

— Fire Brigade intervention

3) Simulation dynamics (profile/time)

— size of fire/smoke, thermal profile

— pressure/velocity, effluent species

— occupant condition and location

— building and content condition

b) Evaluations

1) Thermal + mechanical response

2) Fire spread

c) Processes

1) Heat transfer

— radiation, convection, conduction

2) Mass transfer

— gas flow, flying brands

3) Physical/chemical reactions

— thermal degradation

— phase change

— degradation of strength

— delamination, spalling

— expansion/shrinkage

6.2 Documentation

Appropriate documentation of the model includes such items as the name and version of the model, name of developer(s), and a list of relevant publications that provide additional details on the model. The stated uses, limitations, and results of the model need to be clearly stated. The type of model should be defined. Information should be provided on the scenarios for which evaluation is being sought. Such information includes a description of the scenarios or phenomena of interest, a list of quantities predicted by the model for which evaluation is sought, and the degree of accuracy required for each quantity. Other information includes:

d) the assumptions inherent in the model and the governing equations included in the model formulation, and the numerics employed to solve the equations and the method by which individual solutions are coupled;

e) additional assumptions of the model as they relate to the stated uses or potential uses;

f) the input data required to run the model;

g) property data that are defined with the computer program or were assumed in the model development.

ASTM E 1472, *Guide for documenting computer software for fire models*, provides additional information on the documentation of fire models. Recommended documentation includes technical documentation and a user's manual. It is important to provide the range of applications for the model and the validity over the data range from which the model was developed.

6.3 Deterministic versus probabilistic

Quantitative analyses include deterministic design procedures and probabilistic procedures. Whereas deterministic models predict a single possible result, probabilistic models allow for a range of possible outcomes. In probabilistic models, the objective is to estimate the likelihood of a particular unwanted event. Deterministic models are based on physical, chemical and thermodynamic relationships derived from scientific theories and empirical methods. Probabilistic models are achieved by the use of statistical data regarding the frequency of fire starts and the reliability of fire protection systems, combined with a deterministic evaluation of the consequences of the possible fire scenarios. For the probabilistic model to be integrated with the analytical model(s) of the relevant processes, the following levels can be distinguished[12,22]:

— an exact evaluation of the failure probability, using multi-dimensional integration or Monte Carlo simulation;

— an approximation evaluation of the failure probability, based on First Order Reliability Methods (FORM);

— a practical design format calculation, based on partial safety factors and taking into account characteristic values for action effects and response capacities.

7 Evaluation

7.1 Sources of errors in predictions

Sources of errors in the predictive capabilities of fire models come in various forms[1]. These include errors in

— application of the model,

— assumptions used in the model,

— numerical solutions of the model equations,

— software representation of the model, and

— hardware used to run the software.

Problems associated with the application of the model can include misunderstanding of the model or its numerical solution procedures. The inadequacy of documentation is often cited. There are also straightforward mistakes in inserting input or reading output.

The theoretical and numerical assumptions in a model can only be an approximation of the real world. Inappropriate methods or erroneous assumptions include the use of inappropriate algorithms or wrong physics to describe the fire processes and sub-processes that are being modelled. The incorporation of models as computer software makes it critical that the constants or default values are clearly identified. The use of incorrect or unsubstantiated constants or default values is a source of error, particularly when a model is used outside its initial field of application. Uncertainty in the range of plausible numerical values for parameters is common. Oversimplification of fire phenomena in a model can lead to the omission of critical processes in the model description of the fire phenomena. There should be an independent review of the theoretical basis of a model.

In a review of thermal and structural programs dedicated to fire analysis[2], it was observed that arbitrary and empirical assumptions are often necessary to achieve good correlation between theory and proactivity. Thermal computer codes used boundary condition parameters that were derived empirically and often adjusted arbitrary without appropriate scientific explanations to make the computer predictions fit experimental results. In structural models, there are inadequate inputs of material properties based on inadequate or incomplete material models. It has also been observed that structural analyses in fire are very sensitive to the temperature state of the structure and that many studies do not appear to give sufficient importance to this fact.

Numerical techniques are needed to solve the mathematical equations of the models. Such techniques include finite difference and finite element methodologies. The use of inappropriate numerical algorithms to solve the equation set(s) is another source of error in the predictions. Different numerical methods may be used which give slightly different results and of varying stability. Numerical solutions generally depend on the resolution of the grids of nodes or elements.

Software errors include coding that is not an accurate representation of the model and the numerical solution procedures. Errors in the computer coding of the software represent a significant source for errors in model predictions. The use of a particular software can also be affected by errors in the hardware operating system software or the computer language software used to code the model. Inadequate documentation and the general unavailability of the symbolic coding of computer programs can limit abilities to evaluate software errors.

Hardware is needed to run the software. With progress in computer technologies, this hardware is often a personal computer. Hardware errors include errors in the design or manufacture of the microprocessors.

7.2 Model application and use

Model evaluation starts with documentation of the applicable scenarios. This includes a complete description of the scenarios or phenomena of interest in the evaluation. Such documentation facilitates appropriate application of the model, and aids in the developing realistic inputs for the model and criteria for judging the results of the evaluation.

Model evaluation addresses multiple sources of potential error in the design and use of predictive fire models, including correct model inputs appropriate to the scenarios to be modelled, correct selection of a model appropriate to the scenarios to be modelled, correct calculations by the model chosen, and correct interpretation of the results of the model calculation. Evaluation of a specific scenario with different levels of knowledge of the expected results of the calculation addresses these multiple sources of potential error. It is understood that one or more of these levels of evaluation may be included in a particular model evaluation. These evaluation methodologies include

— blind calculation,

— specified calculation, and

— open calculation.

These methodologies are intended to evaluate the ability of the user to select the appropriate model and input given different levels of problem description and specified input.

In blind calculation, the model user is provided with a basic description of the scenarios to be modelled. For this methodology, the problem description is not exact; the model user is responsible for developing appropriate model inputs from the problem description, including additional details of the geometry, material properties, and fire description, as appropriate. Additional details necessary to simulate the scenario with a specific model are left to the judgement of the model user. In addition to illustrating the comparability of models in actual end-use conditions, this will test the ability of those who use the model to develop appropriate input data for the models.

In specified calculation, the model user is provided with a complete detailed description of model inputs, including geometry, material properties, and fire description. As a follow-up to the blind calculation, this test provides a more careful comparison of the underlying physics in the models with a more completely specified scenario.

In open calculation, the model user is provided with the most complete information about the scenario, including geometry, material property, fire description, and the results of experimental tests or benchmark model runs which were used in the evaluation of the blind or specified calculations of the scenario. Deficiencies in available input (used for the blind calculation) should become most apparent with comparison of the open and blind calculation.

Different models may require substantially different details in the problem descriptions for each of the three levels outlined above. For example, some models may require precise details of geometry while a simple compartment volume may suffice for other models. For some models, a detailed description of the fire in terms of heat release rate, pyrolysis rate, and species production rates are necessary inputs. For other models, these may be calculated outputs. For each of the three levels of evaluation, an appropriate problem description sufficient to allow the problem to be simulated is necessary.

For models for structural fire behaviour, input can include:

— dimensional variations: geometrical parameters;

— load or design variations: level of load and end conditions;

— material variations, including mechanical properties at room temperature of all materials of the structure being modelled; thermal properties and other parameters that affect the temperature or thermal profiles of the structure being modelled; and mechanical properties at elevated temperatures of all materials of the structure being modelled.

While its emphasis is on zone models of compartment fires, information on data required as input to fire models can be found in ASTM E 1591-00, *Standard guide for obtaining data for deterministic fire models*. The need for improved data for input to fire models is also addressed in ISO/TR 15655, *Fire resistance — Tests for thermo-physical and mechanical properties of structural materials at elevated temperatures for fire engineering design*.

7.3 Model theoretical basis

The theoretical basis of the model should be reviewed by one or more recognized experts fully conversant with the chemistry and physics of fire phenomena and the material response to thermal and structural loads, but not involved with the production of the model. This independent review should include:

— an assessment of the completeness of the documentation, particularly with regard to the assumptions and approximations;

— an assessment of whether there is sufficient scientific evidence in the open scientific literature to justify the approaches and assumptions being used;

— an assessment of the empirical or reference data used for constants and default values in the code for accuracy and applicability in the context of the model.

7.4 Model solution

7.4.1 General

The computer implementation of the model should be checked to ensure such implementation matches the stated documentation. Various methods are available to evaluate the mathematical and numerical robustness of the models. These analyses include analytical tests, code checking and numerical tests. For models based on numerical solutions, analytical testing is a powerful way of testing the correct functioning of a model. However, there are relatively few situations for which analytical solutions are known for complex scenarios. Simplifying the desired scenario may provide scenarios for which there are known mathematical solutions of portions of the model.

The code can be verified on a structural basis, preferably by a third party, either totally manually or by using code-checking programs to detect irregularities and inconsistencies within the computer code. A process of code checking can increase the level of confidence in the program's ability to process the data to the program correctly, but it cannot give any indication of the likely adequacy or accuracy of the program in use. A simple evaluation is the comparison of the print-out of the input with the values entered[23].

Numerical techniques used to find solutions for the models are a source of error in the predictions. Numerical tests include an investigation of the magnitude of the residuals from the solution of the system of equations employed in the model as an indicator of numerical accuracy and the reductions in residuals as an indicator of numerical convergence. Such evaluations are discussed in 7.4.2.

7.4.2 Numerical accuracy

Mathematical models are usually expressed in the form of differential or integral equations. The models are in general very complex, and analytical solutions are hard or even impossible to find. Numerical techniques are needed for finding approximate solutions. In a numerical method, the continuous mathematical model is discretized; i.e. approximated by a discrete numerical model. The discretization errors are discussed below.

A continuous mathematical model can be discretized in many different ways resulting in as many different discrete models. To achieve a good approximation of the solution of the continuous models, the discrete model is required to mimic the properties and the behaviour of the continuous model. This means that the discrete solution should converge to the solution (when it exists) of the continuous problem, when the discretization parameters (time step, space mesh, etc.) decrease. This is achieved when the requirements for consistency and stability are met. Consistency means that the discrete model approximates the continuous model well in the sense of some measure, i.e. a norm. The choice of the norm depends on the specific problem. The stability means that the error terms do not increase as the program proceeds.

Often the continuous mathematical model is a set of partial differential equations (PDE). After semidiscretization in space, a set of non-linear or linear ordinary differential equations (ODE) is obtained. Higher-order differential equations can be transformed to systems of first-order equations, and these are considered in the following only first-order equations. The full discrete model is created by discretizing the ODE in the time space (usually finite difference method or finite element method). The resulting non-linear or linear algebraic set of equations is, in turn, solved using appropriate numerical methods (Gauss, Newton, etc.).

Many fire problems involve the interaction of different physical processes, such as chemical or thermal processes and mechanical response. Time scales associated with these processes may be substantially different, which easily causes numerical difficulties. Such problems are called stiff. Some numerical methods have difficulty with stiff problems since they slavishly follow the rapid changes even when they are less important than the general trend in the solution. Special algorithms have been devised for solving stiff problems[24].

Discretization can also result in a stiff discrete model. For example, when heat conduction equations (continuous model described with PDE) are first semidiscretized in space and a stiff ODE is obtained. In this case, the stiffness of the semidiscrete model increases when the spatial discretization parameter (mesh) decreases.

A stiff discrete problem may also arise even though the original continuous problem was not stiff. In non-linear cases, the behaviour and then the stiffness of the model can change over time as the solution evolutes.

Stability must be considered in the analysis and performance of temporal (transient) algorithms to prove the convergence of the solution algorithm. The algorithm for which stability imposes a restriction of the size of the time step is called conditionally stable. An algorithm for which there is no time step restriction imposed by stability is called unconditionally stable. Stable integration gives decaying solutions (this is the case for analytical solutions of the continuous problem ODE). Unstable methods can quickly give unbounded and oscillating numerical solutions for some sizes of time step. It is important to realise that the numerical model can be unstable even when the continuous model is stable. There are, however, cases in which the original continuous model is unstable, and then accurate solutions cannot be expected by any numerical method.

Time integration of the ODE can generally be carried out using two different types of numerical quadrature algorithms, explicit or implicit. In the explicit method, the new values of the solutions are given explicitly in terms of the old values. This is sometimes called time marching and a typical example is the forward Euler algorithm. In the case of implicit methods, the new values depend on the old and the new ones. Examples of implicit methods are backward Euler, Cranck-Nicolson and midpoint family method. Explicit methods are conditionally stable. All the implicit methods are unconditionally stable in the linear case.

Integration of stiff systems of ODE using inadequate algorithms like the unstable or conditionally stable methods may result in unbounded solutions and therefore considerable errors. The stability of the integration, i.e. of the approximate solution, is determined by the more-rapidly-varying solution, even after the solution has effectively died away. This is a generic problem of stiff equations, and one is forced to follow variation in the solution on the shortest time scale to maintain stability of the integration, even though accuracy requirements allow a much larger size of (time) step. A way out of the problem is to use implicit methods.

In non-linear problems, the stability regions of the solution all evolve with the solution itself and the conditions of stability may change. For example, the unconditional stability of the implicit trapezoidal (Crank-Nicolson) integration scheme is not carried over to the non-linear regime. Methods like those of the generalized midpoint family exist, which may preserve unconditional stability also in the non-linear regime.

In addition to the discretization errors, one has to consider also the machine errors caused by the finite accuracy of computer's floating point presentation of numbers. This may raise problems when calculating derivatives with small discretization steps. Round-off error of a difference quotient can lead to catastrophic cancellation, i.e. the error due to subtraction of nearly equal numbers. There may also be a problem especially when the magnitude of variables varies by orders of magnitude. In a good algorithm, the variables are scaled to be of the same order of magnitude if possible.

Because the numerical convergence depends both on the original mathematical model and the method of discretization, no general method exists for checking the consistency and stability in every case. Confidence on the numerical method may be increased by checking the rate of convergence by repeating the calculations with various discretization steps. If the error according to a relevant norm decreases with decreasing step size, the method is consistent. Yet, this does not guarantee the solution found to be a correct one.

In the case of field models, it is important to examine the sensitivity of the solution to grid refinement. This can be an expensive task. Refining a grid by a factor of two in each coordinate direction will increase computational cost roughly by a factor of eight and so it is often necessary to strike a compromise between cost and accuracy. Most general-purpose computer fluid dynamics packages provide diagnostic information on the progress of residual errors for each of the equations solved. However, it is important to be satisfied that the overall mass and energy balances for the whole domain are within acceptable bounds. Compartment mass outflows must balance mass inflows and heat lost into the structure taken together with heat lost from the compartment through its opening must balance that generated by the fire.

It is important to ensure that the solution is “well behaved”. This might include inspection, for example, to ensure that it is free from spurious oscillations, that the characteristics of the fire source, especially its buoyancy flux and flame length, are correctly simulated, and that predicted downstream temperatures away from the areas of chemical reaction are less than those at the source. If problems of this nature do occur, then consideration should be given to reducing the grid spacing and/or time step.

There will be occasions when the computer simulation using field modelling may suggest unexpected behaviour. If a physical simulation were to produce something unexpected, the engineer would exert his ingenuity to explain what has been observed or what has been measured and relate it to the practical problem at hand. However, with a numerical simulation such an eventuality is more disturbing since it can have two explanations: either it is genuine and would have been observed in a physical simulation or, alternatively, it is some sort of misleading numerical artifact.

The possibility of the latter cannot be completely discounted with such complex numerical simulations as those involved in computer fluid dynamics. It is therefore essential to “shadow” the numerical solution, where possible, with known simple calculation methods.

7.5 Comparison of model results

7.5.1 General

Various comparative analyses can be used to evaluate the accuracy of the predictive results of the model. These include comparison with

a) empirical evaluation with standard tests,

b) empirical evaluation with non-standard tests,

c) empirical evaluation with documented fire experience, and

d) evaluation with proven benchmark models including analytical tests and other programs.

Comparison with empirical data is the most common way to evaluate the predictive capability of a model. For structural fire endurance models, results that can be compared include thermal profiles within the components of the structure being modelled, the mechanical behaviour for the well-defined temperature profiles and the fire resistance times. The evaluation of the model needs to be defined in terms of the range of the applications for the model.

Comparison with empirical data is part of most model developments. In evaluations for verification and validation purposes, it is critical that program predictions should be made without reference to the experimental data used for the comparison except for that needed for the required input data. No attempt to adjust a fit between the measurement and the predictions should be made.

For calculation models for structural fire behaviour, the standard test is that of ISO 834 or related national tests. In comparison with such empirical data, the model predictions can be compared with the empirical times for the failure criteria and the related measurement and observations. Where data are available, model predictions should be viewed in the light of the uncertainty in test/experimental data as compared with the uncertainty in the model results that arises due to uncertainty in the model input. In ISO 834 tests, one uncertainty is the definition of the fire exposure used in the experimental test and that used by the models.

When comparison is made with previously published test data, care needs to be taken to ensure that there is sufficient information to ensure that the test closely simulated the scenario of the model. ISO 834 tests conducted for the purpose of establishing the rating of the assembly often do not include sufficient data on the test specimen and the response of the test specimen to the fire exposure. Although key measurements may or may not have been taken, the predictive capabilities can often be assessed by comparing predicted values and measured values of important variables, by comparing key events in the fire, and by comparing key behavioural traits predicted by the model and measured during the simulation. By conducting tests specifically for model evaluation, additional data can be collected.

While the ISO 834 test is often considered a “full-scale” test, tests of actual structures or other non-standard tests may be needed to evaluate the scenarios for which evaluation is sought. In such simulations, the tests should be designed to duplicate, as closely as possible, the salient features of the scenarios for which evaluation is sought. Data should contain sufficient detail (initial conditions, time scales, and so forth) to establish correspondence between predicted and measured quantities. Recently, the behaviour of multistorey steel-framed buildings in fire has been tested and documented in an effect that includes comparison with fire models[25].

Comparison with experimental data involves the validity of the experimental data itself. In a review of thermal models[2], it was concluded that in some cases experimental temperature measurements were in error (due for example to excessive moisture movement around thermocouple tips) and consequently the computer-predicted temperature regimes appeared to be more reliable than experimental data. Thus, the model evaluation includes a thorough evaluation of the experimental data being used in the model evaluation. Uncertainties in the measurements of the empirical data should be accounted for in a systematic and logical manner. This evaluation of the empirical data includes

a) a thorough understanding of the sources of uncertainty in the experiments performed;

b) quantification of these sources of uncertainty;

c) sensitivity analysis to assess the effect of the uncertainty on the predictions;

d) data/program comparison techniques to account for the uncertainty.

See 7.6 for further discussion of this topic.

Comparison with documented fire experience is another option for evaluating a model. When statistical data on the fire experience are used, they must be judged for reliability. Other forms of documented fire experience that can be compared with model predictions include eyewitness accounts of real fires, known behaviour of materials in fires, and observed post-fire conditions.

Proven benchmark models provide another option for evaluating the results of models. Such models can include empirical models and analytical models. Care should be taken to ensure that the benchmark model has been evaluated for the scenarios of interest. The predictive capabilities can be assessed by comparing the predicted values of important quantities, by comparing key events in the fire predicted by both models, and by comparing key behavioural traits predicted by both models. When data are available, model predictions should be viewed in light of the variability of the sensitivity of both model predictions. If the program can be applied to situations for which there is a known mathematical solution, analytical testing provides a powerful way to test the correct functioning of a model. Unfortunately, there are usually few applicable situations for which analytical solutions are known.

An evaluation scheme of computer codes of finite element or finite difference models for calculating temperatures in fire-exposed structures has been published[26]. The scheme starts with an example with an analytical solution to more complex cases with non-linear boundary conditions and material properties varying with temperatures. This scheme does not involve the use of experimental data. The scheme uses repeated analyses with increasing elements or time elements to evaluate the models. Codes yielding results that converge smoothly with increasing elements are considered more reliable. The seven reference scenarios are

a) comparison against analytical results involving constant material properties;

b) addition of non-linear boundary conditions to the problem;

c) addition of non-linear boundary conditions and temperature-dependent thermal properties;

d) addition of latent heat due to water content (common to several major building materials);

e) a composite of steel and concrete;

f) a composite of steel and mineral wool;

g) radiation heat transfer across voids, one and two dimensional.

The development and standardization of reference fire tests, benchmark models, and reference scenarios would improve the reliability of model evaluations.

Simple evaluations of structural models can be useful[23]. Simple questions that can be examined include the following.

— Does a symmetric load case yield symmetric deflections and reactions?

— Does summation of reactions equal summation of load?

— Does the sum of moments, horizontal forces, lateral forces (3-D) and vertical forces equal zero at joints?

— Are deflections consistent with the structural system conditions? For example, are fixed connections shown as displaced?

— What is the orientation of loads? For example, are vertical loads transferred as truly vertical loads on sloped members, such as snow on rafters?

7.5.2 Quantifying model evaluation

Studies[3,6] have provided some guidance on the quantification of the comparison of model predictions with empirical data which are usually described in only subjective qualitative terms such as "good", "reasonable", etc. The appropriate method to quantify the comparison between the two sets of data is not always obvious. The necessary and perceived level of agreement for any predicted quantity is dependent upon the typical use of the quantity in the context of the specific use being evaluated, the nature of the comparison, and the context of the comparison in relation to other comparisons being made. For single-point comparisons such as the time for structural failure, the results of the comparison may be expressed as an absolute difference (model value minus reference value), relative difference ((model value-reference value)/reference value), or other comparison as appropriate. For comparisons of two timed-based curves, appropriate quantitative comparisons depend upon the characteristics of the curves. For steady-state or nearly steady state comparisons, the comparison may be expressed as an average absolute difference or average relative difference.

For rapidly varying comparisons, the comparison may be expressed in terms of a range of the calculated absolute difference or relative difference. The comparison could also be expressed by comparing a time-integrated value of the quantity of interest. Whenever possible, the use of subjective judgements should be avoided and the results of the comparisons should be expressed in quantitative terms.

7.6 Measurement uncertainty of data (from ISO/TR 13387-3)

7.6.1 Introduction

Much of this subclause is taken from reference [27].

This subclause is provided to assist experimenters in expressing the uncertainty of their measurements, and model users in judging the usefulness of experimental data when making an empirical verification of the model. Not all published experimental data will include information on the uncertainty of the data.

In general, the result of a measurement is only the result of an approximation or estimate of the specific quantity subject to measurement, and thus the result is complete only when accompanied by a quantitative statement of uncertainty. The uncertainty of the result of a measurement generally consists of several components which, in the approach used by the International Council on Weights and Measures, may be grouped into two categories according to the method used to estimate their numerical values:

— Type A, those which are evaluated by statistical methods;

— Type B, those which are evaluated by other means.

Uncertainty is commonly divided into two components: random and systematic. Each component that contributes to the uncertainty of a measurement is represented by an estimated standard deviation, termed standard uncertainty, with a suggested symbol u_i, and equal to the positive square root of the estimated variance u_i^2. An uncertainty component in category A can be represented by a statistically estimated standard deviation s_i, equal to the positive square root of the statistically estimated variance s_i^2, and the associated number of degrees of freedom v_i. For such a component, the standard uncertainty $u_i = s_i$. In a similar manner, an uncertainty component in category B is represented by a quantity u_j, which may be considered an approximation to the corresponding standard deviation; it is equal to the positive square root of u_j^2, which may be considered an approximation to the corresponding variance and which is obtained from an assumed probability distribution based on all the available information. Since the quantity u_j^2 is treated like a variance and u_j like a standard deviation, for such a component the standard uncertainty is simply u_j.

7.6.2 Type A evaluation of standard uncertainty

A Type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. An example is calculating the standard deviation of the mean of a series of independent observations using the method of least squares to fit a curve to data in order to estimate the parameters of the curve and their standard deviations. This Technical Report does not attempt to give detailed statistical techniques for carrying out statistical evaluations (see references [27] and [30]).

7.6.3 Type B evaluation of standard uncertainty]

A type B evaluation of uncertainty is usually based on scientific judgement using all the relevant information available, which may include

a) previous measurement data;

b) experience with, or general knowledge of, the behaviour and property of relevant materials and instruments;

c) manufacturer's specifications;

d) data provided in calibration and other reports and, uncertainties assigned to reference data taken from handbooks.

Because the reliability of the evaluation of components of uncertainty depends on the quality of information available, it is recommended that all parameters upon which the measurement depends be varied to the fullest extent practicable, so that the evaluations are based as far as possible on observed data. Whenever feasible, the use of empirical models of the measurement process founded on long-term quantitative data, and the use of check standards and control carts that can indicate that a measurement process is under statistical control, should be part of the effort to obtain reliable evaluations of components of uncertainty.

7.6.4 Combined standard uncertainty

The combined standard uncertainty of a measured result, suggested symbol u_c, is taken to represent the estimated standard deviation of the result. It is obtained by combining the individual standard uncertainties u_i, whether arising from a type A or a Type B evaluation, using the usual method for combining standard deviations. This method is often called the "law of propagation of uncertainty" or the "root-sum-of-squares" method. Combined standard uncertainty u_c is a widely used measure of uncertainty.

7.6.5 Expanded uncertainty

Although the combined standard uncertainty u_c is used to express the uncertainty of many measurement results, what is often required is a measure that defines the interval about the measurement result y with which the value of the measurand Y can be confidently asserted to lie. This measure is termed expanded uncertainty, suggested symbol U, and is obtained by multiplying $u_c(y)$ by a coverage factor, suggested symbol k. Thus $U = kU(y)$ and it can be confidently asserted that $Y = y \forall U$.

In general, the coverage factor k is chosen at the desired level of confidence. Typically, k is in the range 2 to 3. When the normal distribution applies and u_c has negligible uncertainty, $k = 2$ defines an interval having a level of confidence of approximately 95 %, and $k = 3$ defines a level of confidence greater than 99 %. Current international practice is to use the value $k = 2$.

7.6.6 Reporting uncertainty

To report measurement uncertainty, report U together with the coverage factor k used to obtain it, or report u_c. When reporting a measurement result and its uncertainty, include the following information in the report itself or refer to a published document.

— A list of all components of standard uncertainty, together with their degrees of freedom where appropriate, and the resulting value of u. The components should be identified according to the method used to estimate their numerical values (statistical or other means).

— A detailed description of how each component of standard uncertainty was evaluated.

7.7 Model sensitivity

Deterministic models involve uncertainties. A sensitivity analysis of a model is a study of how changes in model parameters affect the results generated by the model. Model predictions may be sensitive to uncertainties in input data, to the level of rigor employed in modelling the relevant physics and chemistry, and to use of inadequate numerical treatments. A well-designed and executed sensitivity analysis serves

a) to identify the dominant variables in the models,

b) to define the acceptable range of values for each input variable,

c) to demonstrate the sensitivity of output variables to variations in input data,

d) to inform and caution any potential users about the degree and level of care to be taken in selecting input and running the model, and

e) to provide insights as to which parameters should be monitored in large-scale fire experiments.

As noted in BS DD 240-1, *Fire safety engineering in buildings — Guide to the application of fire safety engineering principles*, the objective of a sensitivity study should be not simply to check the accuracy of the results but also to investigate the criticality of individual parameters. A sensitivity study will act as a guide to the level of accuracy required of the input data. For example, it may be important to establish how critical a system is to the final consequences. If a single system or assumption is shown to be critical to the overall level of safety achieved, consideration can be given to providing a degree of redundancy in the design or to carrying out a probabilistic study.

Fire models are typically based on a system of ordinary differential equations of the form

$$dz/d\tau = f(z, p, \tau) \; z(\tau = 0) = z_o \quad (1)$$

where

z (z_1, z_2,…., z_m) is the solution vector for the system of equations (e.g. mass, temperature, or volume);

p (p_1, p_2,…, p_n) is a vector of input parameters (e.g. room area, room height, heat release rate);

τ is time.

The solutions to these equations are, in general, not known explicitly and must be determined numerically. To study the sensitivity of such a set of equations, the partial derivatives of an output z_j with respect to an input p_i (for j = 1, …, m and i = 1, ...,n) should be examined.

The selection of parameters to be investigated will be aided by the knowledge and familiarity of the investigator with the thermal and mechanical behaviour of materials.

Inputs to models include

— scenario specific data, such as the geometry of the domain, the environmental conditions, and specifics of the fire description;

— property data, such as thermal conductivity, density and heat capacity;

— numerical constants, such as turbulence model constants, entrainment coefficients and orifice constants.

A distinction must also be made between parameters which are internal and those which are external to the model. The former provide an insight on how well the physics and the mathematics utilized in the model reflect real fire behaviour and should be subject to verification. In some types of model, internal parameters may be open to manipulation by the user. In particular, for CFD-field models the numerical factors such as relaxation, numerical grid and number of iterations are internal parameters. The latter are those parameters which the user can manipulate as inputs. External parameters can be partitioned as follows.

— Geometrical: structure basic dimensions.

— Fire scenario: derived from the standard time-temperature curve or methodologies for natural fires and the distribution of fuels.

— Thermophysical: the thermophysical properties of the materials can influence the development of the temperature profiles, hence properties such as conductivity, specific heat and density are necessary input.

— Mechanical: The structural behaviours depend on the physical and mechanical properties of the materials.

Conducting a sensitivity analysis of a complex fire model is not a simple task. Conducting a sensitivity analysis of a fire model is not a simple task. Many models require extensive input data and generate predictions for multiple output variables over an extended period of time[31,32]. A practical problem, to be faced when designing a sensitivity analysis experiment, is that the number of model runs required will rapidly increase with the number of input parameters and number of independent variables considered. Hence a full factorial experiment may be prohibitive in terms of man hours expended for the return gained.

In many cases, partial factorial experiments will be adequate for the purpose of obtaining information on the effect of varying the input parameters and consequential interactions considered important. In this case, third- and higher-order interactions may often be ignored. For sensitivity analysis of models with large numbers of parameters, efficient methods are available to conduct the analysis with a manageable number of individual model simulations[33]. For highly non-linear fire models, the method of choice is most often Latin Hypercube sampling.

With Latin Hypercube sampling, the possible range for input parameter is divided into N intervals of equal probability. For each input parameter, one value is randomly chosen within each of the N intervals. From the resulting N possibilities for each input parameter, one value is randomly selected. This set of values is used for the first simulation. The preceding is repeated N times to generate N sets of parameters for N total model simulations. Software is available which can calculate parameter values for a Latin Hypercube sampling[34].

Several methods of sensitivity analysis have been applied to fire models[4,32,35]. The one chosen for use will depend upon the resources available and the model being analysed. Two common methods of analysis are global methods and local methods.

Global methods produce sensitivity measures, which are averaged over the entire range of input parameters. Global methods require knowledge of the probability density functions of the input parameters, which in the case of fire models is generally unknown.

Local methods produce sensitivity measures for a particular set of input parameters and must be repeated for a range of input parameters to obtain information on the overall model performance. Finite difference methods can be applied without modifying a model's equation set, but require careful selection of input parameters to obtain good estimates. Direct methods supplement the equation set solved by a model with sensitivity equations derived from the equation set solved by the model[36]. The sensitivity equations are then solved in conjunction with the model's system of equations to obtain the sensitivities. Direct methods must be incorporated into the design of a fire model and are not often available for already existing fire models. There are several classes of local methods which are of interest. Using the nomenclature of Equation (1), these are outlined below.

Finite difference methods provide estimates of sensitivity functions by approximating the partial derivatives of an output z_i with respect to an input p_i as finite differences:

$$\frac{\partial z_j}{\partial p_m} = \frac{z_j(p_1, p_2, \ldots, p_m + \Delta p_m, \ldots, p_k) - z_j(p_1, p_2, \ldots, p_m, \ldots, p_k)}{\Delta p_m} \tag{2}$$

where

j is 1, 2, …, n;

m is 1, 2, …, k.

This method is easy and straightforward to implement. However, as with any finite difference method, the choice of Δp_m is pivotal in obtaining good estimates. To determine the $n \cdot k$ first-order sensitivity equations requires k + 1 runs of the model. These may be run simultaneously as a larger system or in parallel.

Direct methods derive the sensitivity differential equations from the model's system of ordinary differential equations:

$$\frac{d}{dt}\frac{\partial z_j}{\partial p_m} = \frac{\partial f_j}{\partial p_m} + \sum_i \frac{\partial f_j}{\partial z_i}\frac{\partial z_i}{\partial p_m} \qquad (3)$$

where

j is 1, 2, …, n;

m is 1, 2, …, k.

These equations are then solved in conjunction with the model's system of differential equations to obtain the sensitivities. To compute the $n{\cdot}k$ first-order sensitivities requires one model run. These may be incorporated directly into the model and solved as a single, coupled set of $n + (n{\cdot}k)$ differential equations[47] or decoupled solving the model equations and the sensitivity equations iteratively using the model's solution and an appropriate interpolation scheme[38].

With the Response Surface Method, an appropriate vector of functions is fit to a selected set of model runs. The resulting metamodel is then assumed to behave in the same manner as the model. By appropriate choice of functions, the resulting metamodel is simpler and easier to analyse than the actual model. The equations are then solved to perform a sensitivity analysis on the metamodel. The Jacobian of the metamodel solution represents the sensitivity equations.

Examples of sensitivity analyses for compartment zone models are given in reference [9].

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ICS 13.220.01

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