Using Results from Performance-Based Test Methods for Material Flammability in Fire Safety Engineering Design

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ABSTRACT: In order to be able to apply performance design procedures with regard to material flammability in building design, a comprehensive and coherent philosophy on material reaction-to-fire must be developed. This paper gives a general discussion on performance-based design and performance-based test methods for material flammability. A number of end-use scenarios and critical conditions are discussed. The dominant physical mechanisms leading to these critical conditions are described, indicating which material properties must be measured. Examples of how the properties can be used in mathematical modeling to predict critical conditions in full-scale tests are given, showing that these properties are indeed the desired product of the test methods. Finally, recommendations are given for the development of the methods so they can be used in fire safety engineering design.

KEY WORDS: performance-based, test methods, material properties, reaction-to-fire.

PRESCRIBED TEST METHODS

THE REACTION-TO-FIRE OF products used in buildings has been a concern for legislators and authorities since the advent of building fire safety regulations. In recent years, there has been an ongoing intense activity to develop reaction-to-fire test methods and ranking systems.

Some proposed testing and ranking systems for the reaction-to-fire behavior of products have been based on test methods which give, as output, certain rating terms or arbitrary numbers. As an example, such a

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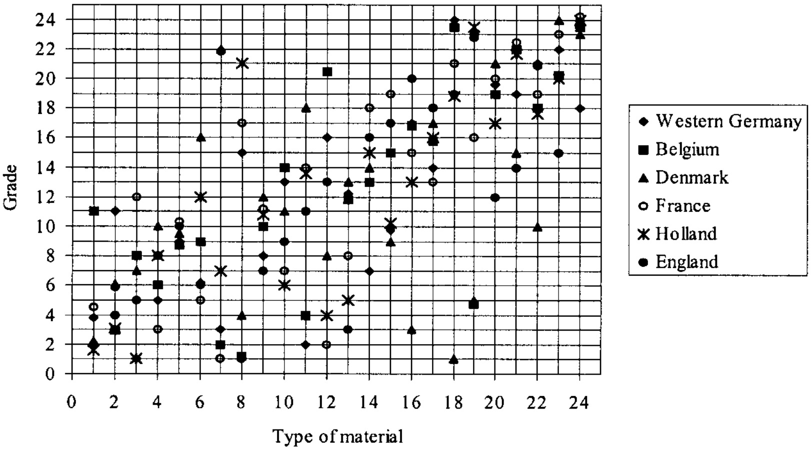

Figure 1. The ranking of 24 lining materials determined at six national testing laboratories in Europe, according to each nation's regulations in the 1970s [1].

test method may report a "burnt length" at a given time, or the time until the flame has reached a given length. Such numbers have a very weak or very uncertain link to material properties and the dominant physical processes involved. They cannot be used for rational classification nor for design calculations. However, such test methods have been used, in conjunction with empiricism, to rank materials, but this ranking has a questionable basis.

Figure 1 shows the results from a survey, conducted in the 1970s [1], of several European test methods that were used to rank the flammability of lining materials used in buildings. The tests were carried out in six national laboratories according to each country's test and classification method. A low grade indicates high risk. The figure shows that there is an alarming spread in the results. Material 18, for example, was considered the best material tested in Germany, while it was classed as the worst in Denmark.

All of the test methods used in Figure 1 were prescriptive test methods. The very undesirable state of affairs led to a very comprehensive study, funded by the Commission of the European Communities, on how scientific tools could be used to classify construction products with regard to their behavior in fire situations. The study recommended extensive, long-term research and testing to be carried out [2].

The Single Burning Item Test (SBI)

The pressing need for a harmonized European approach to the reaction-to-fire classification of products was such that the recommendations for long-term research in Reference [2] could not be followed. In 1994, it was agreed that all member countries in the European Community should have the same test procedures and the same classification system for surface lining materials used in buildings [3]. The classification system is mainly based on the FIre Growth RAte (FIGRA) index, which is calculated using the parameters from the main test method, the Single Burning Item (SBI) test [4].

While the ambition of the SBI test developers was to measure such variables as time to ignition, flame spread and heat release rate, the method cannot provide a meaningful measure of these. To try to observe the occurrence of ignition or the position of a flame front behind a large gas burner flame is not very meaningful. Also, the heat release rate of a material must be measured per unit area if the measurement is to be used in an engineering fashion. The SBI method measures heat release rate as the pyrolyzing area increases; the data is therefore only applicable to the SBI scenario and cannot be used in engineering. Neither can the data be used as a reference scenario for a real room fire since the apparatus has little relation to a typical room.

Convincing regulators in European countries to change their national testing and classification system, in order to agree on a single harmonized system, was an onerous and time-consuming task. In this sense, the development of the SBI test method and the European classification system must be seen as a great political success. However, in terms of science, engineering and performance-based design, the SBI method has been severely criticized [5]. The method cannot be said to be a performance-based test method, since no material properties can be directly derived from the test procedure. However, Sundstrom et al. [6] have shown that it is quite possible to link performance in the Cone Calorimeter [7] (and therefore the Room Corner Test [8]) to performance in the SBI test through the FIGRA value.

PERFORMANCE-BASED TEST METHODS

During the last few decades, the rapid development within modern building technology has resulted in unconventional structures and design. At the same time, there has been a rapid progress in the understanding of fire processes and their interaction with humans and buildings. Advancement has been particularly rapid where analytical fire modeling is concerned. Several different types of such models, with a varying degree of sophistication, have been developed in recent years and are used by engineers in the design process.

As a result, there is a worldwide movement to replace prescriptive building codes with ones based on performance. In this context, there is a considerable interest internationally to develop performance-based test methods and classification systems for building products. The interest has specifically been directed towards lining materials for interior surfaces, but studies of other fixed interior products in buildings, such as floorings and cables, have also been conducted. This paper describes methods developed for interior lining materials as a good example of how performance-based test methods for reaction-to-fire of products can be developed.

Criteria for Performance-Based Test Methods

The CIB (Conseil International du Bâtiment) has, for over two decades, been working with the performance concept in building design. In a publication from 1982, CIB Working Commission W060 discusses a number of criteria for performance test methods [9]. These criteria can be summarized as follows:

- Conditions of test, under which the behavior of the article is being assessed, must be realistic in relation to the expected conditions of use, or related to them in some known way.
- There needs to be a clear scientific basis for relating the results of performance testing under simplified conditions to conditions in practice.
- It is important to consider – and to reconsider – whether the method will be suitable for predicting the behavior of the product under real conditions of use.

The report [9] also states that although it may theoretically be desirable that a performance-based test method should be independent of the material or construction tested, it is difficult to respect this principle in all cases. It further mentions that the method should ideally be simple but that simplification should not go so far that the method fails to provide a reasonable simulation of conditions of use.

Philosophy for Reaction-to-Fire Test Methods

In 1995 CIB organized a workshop on “New Developments in Performance Test Methods” [10], where Karlsson and Kokkala [11] discussed developments in the Nordic countries (Denmark, Sweden, Norway and Finland) with respect to performance-based test methods for assessing fire safety of products. The Nordic development shall be briefly described since the process is relatively typical of the efforts being made internationally.

The Nordic philosophy on material reaction-to-fire is based on a long tradition of harmonizing test methods and regulations. In addition to testing, the use of calculation methods has been promoted. In many cases, the use of calculation methods is already recognized in the national building regulations. To minimize the problem of getting input data for calculations, the policy of the Nordic fire researchers has been to support methods where the output data can be used both to classify products for prescriptive codes and as input data in calculations.

In the late 1980s Wickström [12] compared testing of the mechanical behavior of building elements with the reaction-to-fire of interior surface lining materials. His comparison is schematically shown in Figure 2. The images on the left-hand side (mechanical behavior) show how the real end-use condition is simplified and represented by a beam with supports, tested in full scale. A part of the material can be tested in small scale to give material properties. These properties can then be used as input to a mathematical model to calculate critical conditions in large scale and the results compared to design criteria.

Similarly, for surface lining materials, the real end-use condition is represented by a full-scale test method with lining material attached to the enclosure surfaces. An ignition source is provided and time to flashover, t_{fo},

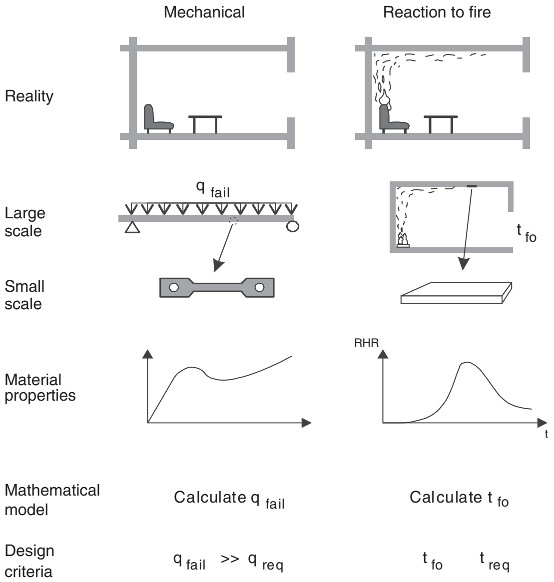

Figure 2. *A schematic comparing the philosophy for testing mechanical behavior of building elements with that of the reaction-to-fire of interior surface lining materials [12].*

assumed to be the critical condition, is recorded. A piece to the material is tested in small scale to give material properties that are used in a mathematical model to calculate full-scale behavior.

A Nordic fire research program, EUREFIC (European Reaction to Fire Classification) was carried out in 1989–1991 in order to speed up the development of performance-based test methods for reaction-to-fire of interior building products [13]. The program focused on two test methods: the full-scale ISO 9705 – Room Corner Test [8] and the bench-scale ISO 5660 – Cone Calorimeter Test [7]. The main motivation for this program was to facilitate a change towards technically more advanced methods.

It is evident that there are products that cannot be reliably tested in small scale. This may include some composite materials and phenomena such as melting and dripping and mechanical failure of the product. These materials will need to be tested in a large-scale reference scenario.

End-Use Scenario, Critical Conditions and Controlling Processes

Before any performance-based test method can be devised, the details behind the testing philosophy must be developed. Specifically, in order to devise a rational ranking system for the flammability of products, which to some extent reflects the hazards encountered in an end-use scenario, one must

- define one or more end-use scenario (large room, small room, ignition source, openings, etc.) and develop a standardized test for that purpose. The ISO Room Corner test has already gained status in a number of countries as a reference scenario for small rooms.
- define one or more limit states or critical conditions (e.g., time until a certain temperature is attained, time to flashover, time until a certain concentration of gases is attained, etc.). Time to flashover has been used as a limit state in the Nordic countries.
- use knowledge of the end-use conditions and limit states to define the controlling physical mechanisms involved. Time to ignition and upward flame spread velocity are very dominant for most scenarios and these processes are described further in this paper.
- design a performance-based bench-scale test method that gives as results actual or estimated flammability properties which reflect the controlling physical mechanisms involved and can be used as input for engineering methods. This paper shows how results from the Cone Calorimeter can be used for this purpose.
- use engineering methods and simplifications in order to allow practical use of the bench-scale test results to estimate hazard in the end-use

condition. A number of models of varying degree of sophistication and applicability are available; both simple and more complex models are described in this paper.

MODELS FOR CALCULATING UPWARD FLAME SPREAD AND FIRE GROWTH

In the last decade several groups of scientists, working separately in various countries, have developed flame spread theories that can be used in an engineering fashion to calculate upward flame spread and the resulting fire growth. These methods are of various degrees of sophistication and complexity. Some give approximate answers for specified end-use scenarios, can be used by others than the developers and require simple input. Other methods are more general, but may require expert knowledge and a large amount of input data.

Mainly two types of methods for such predictions, in practical end-use scenarios, have been proposed in the literature. Firstly, purely thermal models for upward flame spread have been used, with input data from the Cone Calorimeter, to predict flame spread in large scale and the resulting heat release rate. Secondly, more fundamental work has been carried out using CFD (computational fluid dynamics) models and pyrolysis models to predict fire growth. These efforts will be discussed further in this section.

Upward Flame Spread Models Based on Thermal Theories

Ignition of a solid material can be defined as the attainment of a given surface temperature, called ignition temperature. Purely thermal theories can then be used to calculate surface temperatures on a solid and, as soon as an element reaches the ignition temperature, that element is assumed to be pyrolyzing. Often, the element is then assumed to release a certain amount of energy, usually linked to heat release rate measurements from the Cone Calorimeter. Such an approximation eliminates the need for calculating the mass flow rate of combustion gases from the solid element and no account of chemical kinetics has to be taken.

Many different approaches to such modeling have been made where the results have been compared to experiments involving practical building materials. All of these require that the flame morphology, specifically the flame length, be estimated as well as the heat flux from the flame to the solid materials. It is generally difficult to estimate these variables and many researchers have therefore opted for making relatively simple assumptions with respect to flame lengths and flame heat fluxes.

Hasemi [14] used a variable flame heat flux to analyze temperature rise of the unburned fuel ahead of the pyrolysis front. Delichatsios et al. [15, 16] and Beyler et al. [17] also used expressions for a variable heat flux over the flame height to calculate the upward flame spread velocity and fire growth.

One of the most straightforward approaches is characterized by assuming a simple relationship between flame length and heat release rate and assuming a constant flame heat flux over this length, as Saito et al. [18] did. This led to an analytical mode for upward flame spread velocity involving a Volterra-type integral. Thomas and Karlsson [19] solved the Volterra equation and Karlsson [20] used this approach to develop a model for predicting flame spread and fire growth in several geometries, including the Room Corner test. This model requires that the material be tested in the Cone Calorimeter at a number of different heat flux levels in order to derive an apparent thermal inertia, $k\rho c$, which is used to calculate time to ignition. The heat release rate data from the Cone Calorimeter, and the $k\rho c$ value, is then used to calculate flame spread velocity and heat release rate in the large-scale test (e.g., the Room Corner test).

Several models of this type have been described in the literature and only a few will be mentioned here as examples. Cleary and Quintiere [21] developed a method that allowed both upward and lateral flame spread to be calculated, using data from the Cone Calorimeter and the LIFT apparatus. Baroudi and Kokkala [22] developed a computer program to solve the Volterra-type integral equation and Kokkala and Baroudi [23] tested it against experiments, using Cone Calorimeter data as input.

Gojkovic and Hultquist [24] incorporated this flame spread model into a two-zone model and evaluated it against experiments. They found that the weakness of the flame spread model was that the values of a number of constants and parameters (such as flame height parameter, initial pyrolysis height parameter, heat flux from the gas burner and heat flux from the wall flame) were uncertain.

In order to arrive at the optimal values for these parameters, North et al. [25] used an analytical version of the flame spread model in conjunction with the computer program @Risk and carried out a comprehensive sensitivity analysis. Experimental data from 47 materials tested in the full scale Room Corner test were used as a basis for the simulations to optimize the model performance.

A summary of results for two models will be presented. Both models are based on the same upward flame spread theory but differ in the required input data. Model 1 is the one developed by Karlsson [20,26], Model 2 is the one developed by North et al. [25].

MODEL 1

This model requires that the material be tested in the Cone Calorimeter at a number of different heat flux levels in order to derive an apparent thermal inertia, $k\rho c$, which is used to calculate time to ignition. This requires at least four, preferably more, tests to be carried out in the Cone Calorimeter. The heat release rate data from the Cone Calorimeter, and the $k\rho c$ value, is then used to calculate flame spread velocity and heat release rate in the large-scale test (e.g., the Room Corner test).

Karlsson [26] used 22 different Room Corner test experiments and compared calculated and experimentally measured heat release rates. The experimental data originates from two series of experiments, the S-series [27] and the E-series [12]. Figure 3 shows calculated and experimentally measured time to flashover for all 22 materials tested. Only two out of 22 materials deviate significantly. Some of the materials did not go to flashover in the Room Corner test and this is indicated by the longest bars in Figure 3.

MODEL 2

This model only requires that the material be tested once in the Cone Calorimeter, at an incident heat flux of 50 kW/m^2. Instead of deriving the

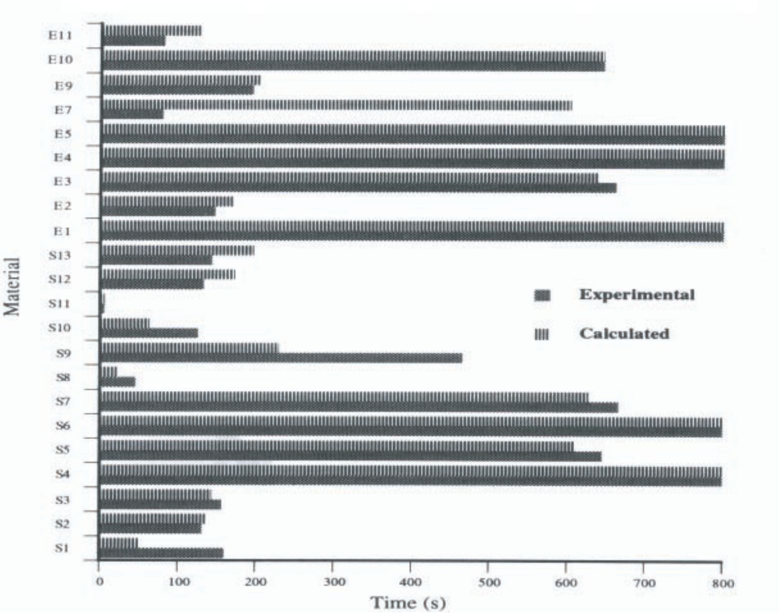

Figure 3. *Model 1: Calculated and experimental time to flashover in the Room Corner test for 22 different surface lining materials (no flashover after 800 s) [26].*

$k\rho c$ parameter from several such measurements, North et al. [25] used all available ignition data to derive a simple regression equation to calculate time to ignition at various heat fluxes. They found that, for the majority of materials, the expression $t_{ig} = 113\rho/(\dot{q}''_e)^2$ was appropriate, where ρ is the material density and $\dot{q}''_e$ is the expected incident heat flux in the full-scale scenario to be simulated.

The computer program @Risk was then used to optimize four constants in the upward flame spread model; the flame height coefficient, K; the initial pyrolysis height, x_{po}; the incident heat flux from the burner; and the incident heat flux from the wall flame. As a result, a simple engineering methodology was developed for calculating upward flame spread and heat release rate in a number of important scenarios. By using only one experiment from the Cone Calorimeter, the model can be used to calculate the heat release rate, flame height and other important parameters in a number of different full-scale scenarios.

Figure 4 shows calculated and experimentally measured time to flashover for 47 materials tested, using data from a single Cone Calorimeter experiment. The results show an overall good comparison, significant deviation is noted for some thermoplastic materials. Note that in the test method the heat source is changed from 100 kW to 300 kW at 600 s, but the current analysis was only carried out for the first 600 s.

Many other models than those mentioned above have been used for predicting full-scale fire growth using input data from the Cone Calorimeter. This section has concentrated on upward flame spread on practical surface lining materials, and results have only been shown displaying their behavior in the Room Corner test. Many other applications have been developed: Grant and Drysdale [28] used these methods to model flame spread in warehouse fires; Van Hees and Thureson [29] have used this technique for predicting flame spread on cables; and Kokkala and Baroudi [23] to study flame spread on vertical wooden materials, to name only a few studies.

Flame Spread Models in CFD Codes

The most sophisticated deterministic models for simulating enclosure fires are termed CFD models (Computational Fluid Dynamics models). The volume under consideration is divided into a very large number of sub-volumes and the basic laws of mass, momentum and energy conservation are applied to each of these. A handful of such models have been specially developed to simulate fires in compartments.

Since CFD models allow variables to be calculated locally in a very fine mesh, there is no need to make the very rough assumptions on flame height

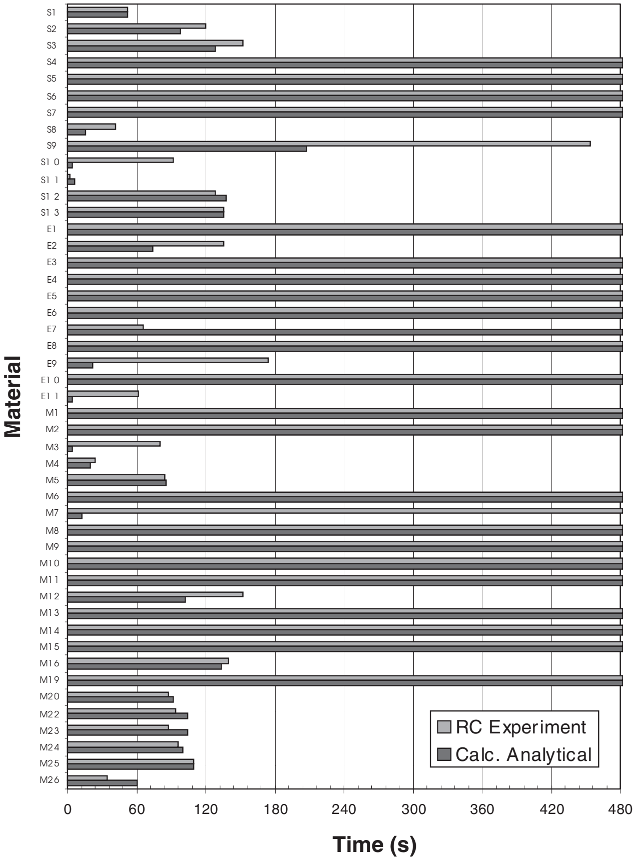

Figure 4. *Model 2: Calculated and experimental time to flashover in the Room Corner test for 47 different surface lining materials (only the first 480 s shown) [25].*

and heat flux made by the thermal models. This opens up possibilities for more sophisticated models, both for calculating solid material temperatures and mass flow rate of pyrolysis products from the solid material and the subsequent combustion. However, for some applications, data from the Cone Calorimeter can be used instead of calculating the pyrolysis and the combustion process.

As an example of this approach, Yan and Holmstedt [30] presented a pyrolysis model embedded in a CFD code for predicting flame spread on a vertical PMMA slab. Both the turbulent combustion of the gas phase and the pyrolysis of the solid fuel were numerically simulated. Tuovinen et al. [31] have implemented this model into the well-known CFD code SOFIE [32] and tested it for other types of materials, showing good results.

The model is based on a one-dimensional numerical heat transfer model that uses a standard numerical solver for the heat conduction equation. Each numerical heat conduction strip is then divided into a number of substrips to which a simple pyrolysis model is applied. The input parameters with respect to the thermal and pyrolysis model are the ignition temperature, pyrolysis temperature, heat of pyrolysis, heat of combustion, virgin density, char density, specific heat and thermal conductivity.

Alternatively, the flame spread model can directly use heat release rate data from the Cone Calorimeter for each cell at the surface of the material. The pyrolysis model must therefore not be applied which simplifies the input data requirements substantially.

Figure 5 shows the results when the model calculations were compared to two identical experiments carried out by Yan [33] and Andersson [34] in a 1/3 scale of the Room Corner test, where particle board was attached to both walls and ceiling. The figure shows the calculated heat release rate inside the room (marked "inside") and the total heat release (marked "total"), since some of the heat is released outside the room. The figure also shows the difference between using the full pyrolysis and combustion model (marked "p") and using Cone Calorimeter results to estimate heat release rate from each solid element (marked "c").

The flame spread and pyrolysis models used in CFD codes are still being developed and they have not been put to much practical use yet. However, this type of flame spread model will in the near future be an invaluable tool for researchers and engineers, since it can be used for a very wide variety of end-use scenarios and a wide variety of products.

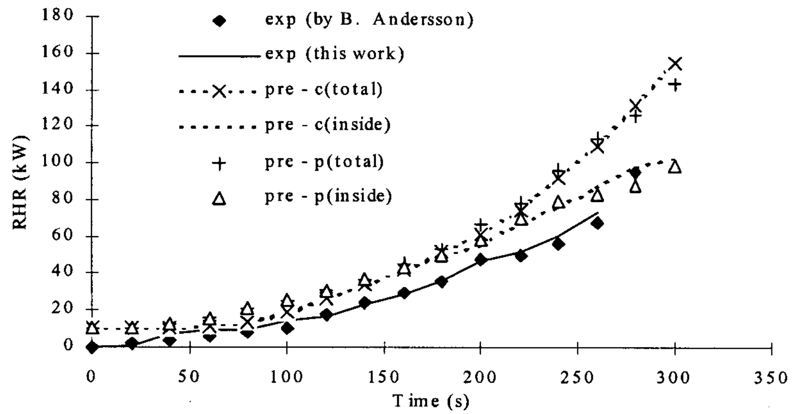

Figure 5. Calculated and measured heat release rates in the 1/3 scale scenario. The symbol (c) denotes using Cone Calorimeter data as input and (p) using the pyrolysis model [33].

Using Upward Flame Spread Models in Fire Safety Engineering Design

During the last few decades, much work has been concentrated on developing performance-based test methods for predicting reaction-to-fire behavior of products in large-scale situations. Much less work has been concentrated on developing models that allow data from bench-scale methods to be used for full-scale calculations. Many of the available methods have only been validated for a very narrow range of materials and often only a single large-scale scenario.

In order to make the calculation methods available to engineers, the following points must be considered:

- Scientists should not only concentrate on further development of existing models, but also test these against a wide variety of materials. Further, they should make the models available to engineers, with clear guidelines on applicability, required input and resulting output.
- Experiments must be conducted in a wider variety of full-scale scenarios and models must be evaluated against these in order to pave the way for the use of models in the design process.
- Critical conditions for a number of large-scale situations should be arrived at. This may be expressed as a given maximum allowable heat release rate in a certain size compartment. Also, a limit on flame height may be used as a critical condition, since a flame that reaches a ceiling will start to cause relatively high radiation flux towards objects on the floor. Several different types of full-scale scenarios (small room, corridor, large room, high ceiling, low ceiling, etc.) must be considered in conjunction with the position of combustible materials in the compartment.

It is obvious that considerable work on making models available must be conducted before engineers can, in any wide sense, start to use these as a basis for choosing appropriate interior building materials.

CONCLUSIONS

One of the major differences between a prescriptive rule and a performance requirement stems from the method of assessing its fulfillment. For the prescriptive rule, one must observe and verify that every detail in the prescriptive legislation is observed. This can be done during the design process, the construction process or after construction is completed. For the performance criterion, this must be done using evaluation tools that measure or predict the relevant properties and performance level. Such tools are test methods and simulation models and the models will need material parameters as input. The material parameters must be measured by carefully developed test methods and the results from the test methods must be relevant to the end-use condition. Testing and modeling nearly always involves considerable approximation or simplification of real conditions of use.

This paper has discussed the need for developing a sound engineering philosophy for testing and ranking products with respect to fire hazard and given certain recommendations on how to achieve this goal. Further, a number of mathematical models of various degrees of sophistication and complexity have been described. Some require simple input data and give approximate answers for certain end-use conditions, others are more general but require non-standard input data and expert knowledge.

The existing models must be developed further. However, in order to pave the way towards performance-based design with regard to the use of interior building materials, a far more urgent task is to widen the validity of the models and increase their user-friendliness and availability to engineers.

The purpose of this paper has been to discuss the underlying philosophy of performance-based test methods and emphasis has been put on describing, as an example, a certain suite of tests that can be said to constitute such a system for material flammability of building materials. Note that several other test methods (large scale, intermediate scale and small scale), that have not been mentioned here, could be used for such a purpose.

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