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Tuula Hakkarainen

Studies on fire safety assessment of construction products

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Studies on fire safety assessment of construction products

Tuula Hakkarainen

VTT Building and Transport

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Post-flashover flames emerging from a fire room opening in a full-scale facade fire test (courtesy of VTT Building and Transport).

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Abstract

Various aspects of assessing the fire safety of construction products related to the initiation and development of fire and the determination of toxic smoke gases have been studied. The primary objective has been to provide new information on the subject in the context of the harmonized European fire classification system as well as related to more general fire safety aspects.

Two models for predicting the results of a European intermediate-scale reaction-to-fire test, the SBI test, have been introduced. The essential feature of the models is that only the heat release rate data of a single cone calorimeter test at the heat exposure level of 50 kW/m^2 is required as input for predicting the performance of a product in the Euroclass system. The models gave a correct classification for 80–90 % of the products studied. The models provide practical tools for product development and quality control.

The fire test methods and classification parameters of the Japanese and European fire classification systems of surface linings are different. Owing to the common reference scenario, the classification systems are still strongly consistent for the majority of products. Inconsistencies can be recognized by examining the product type and composition and by considering the special features of the main fire tests used in the classification. Modelling of SBI test results on the basis of cone calorimeter data provide a link between the Japanese and European fire classification systems.

An optimised sampling system for smoke gas measurements in the fire test environment using the Fourier transform infrared (FTIR) spectrometry has been defined. Recommendations related to data analysis, calibration and software have been given. The FTIR technique has been verified against alternative

determination methods of smoke gases in the fire test environment. The precision of the method has been determined in an interlaboratory trial.

The fire behaviour of wooden facades in multi-storey houses has been studied in two different fire scenarios: an external fire and a post-flashover compartment fire. Fire tests of wooden facades with different materials, surface treatments and structural details have been performed on the intermediate and large scales. Acceptance criteria for the facades of sprinklered and unsprinklered buildings have been proposed in terms of heat flux, fire spread and falling parts. The basic principles of the criteria are applicable also to other facade fire scenarios under various test conditions.

Post-flashover gas temperatures and charring behaviour of timber construction compartments have been studied in large-scale fire experiments. The parametric temperature-time curves presented in the draft for the revised Eurocode 1 were found to overestimate the gas temperatures in timber construction compartments. The gas temperature development in the test rooms was found to be dependent on the contribution of wooden enclosure surfaces on the production of pyrolysis gases. The proportions of pyrolysis gases burning inside and outside the fire compartment were estimated considering the energy balance. The onset of charring of timber structures exposed to the natural fire conditions used in the experiments could be delayed significantly by using sufficient gypsum plasterboard protection. The overall charring rate was notably reduced if the protective layer remained in its position throughout the most intensive burning period of the movable fire load. After that period, the burning of the ceiling and walls could not maintain the high temperature level inside the room. Due to the decreasing temperature, the heat flux incident on the wooden surfaces was reduced leading to lower charring rates.

Preface

This work has been carried out under the auspices of the Technical Research Centre of Finland (VTT).

I wish to express my sincere gratitude to Prof. Matti Kokkala, my supervisor, for his guidance and encouragement throughout the work. I am most grateful to Dr Esko Mikkola, head of the Fire Research group, for his advice and for providing the flexible research environment that made this work possible. I also wish to thank Prof. Rolf Hernberg for his supervision during the completion of this thesis.

I am thankful to all my co-authors and colleagues involved in this work in Finland and abroad for their invaluable contributions. The efforts of Dr Yoshihiko Hayashi during my stay in Japan are especially appreciated and gratefully acknowledged. I wish to thank all my colleagues in the Fire Research and Fire Testing groups of VTT Building and Transport for creating a pleasant and friendly working atmosphere.

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I am grateful to my parents Taina and Pertti Hakkarainen for their endless trust in my abilities. Last but not least, I wish to thank my husband Vesa Sirén for his constant encouragement and understanding throughout this work.

Helsinki, February 2002

Tuula Hakkarainen

List of publications

This thesis is based on the following publications. In the text, the publications are referred to by Roman numerals.

I Hakkarainen, T. & Kokkala, M. A. Application of a one-dimensional thermal flame spread model on predicting the rate of heat release in the SBI test. Fire and Materials, 2001. Vol. 25, No. 2, pp. 61–70.

II Hakkarainen, T. Rate of heat release and ignitability indices in predicting SBI test results. Journal of Fire Sciences, 2001. Vol. 19, No. 4, pp. 284–305.

III Hakkarainen, T. & Hayashi, Y. Comparison of Japanese and European fire classification systems for surface linings. Fire Science and Technology, 2001. Vol. 21, No.1, pp. 19–42.

IV Hakkarainen, T., Mikkola, E., Laperre, J., Gensous, F., Fardell, P., Le Tallec, Y., Baiocchi, C., Paul, K., Simonson, M., Deleu, C. & Metcalfe, E. Smoke gas analysis by Fourier transform infrared spectroscopy – Summary of the SAFIR project results. Fire and Materials, 2000. Vol. 24, No. 2, pp. 101–112.

V Hakkarainen, T. & Oksanen, T. Fire safety assessment of wooden facades. Accepted for publication in Fire and Materials, 2002.

VI Hakkarainen, T. Post-flashover fires in light and heavy timber construction compartments. Accepted for publication in Journal of Fire Sciences, 2002.

Author's contribution

The research reported in this thesis was mainly carried out under the auspices of the Fire Research group of VTT Building and Transport, Finland, during 1994–2001.

Paper I deals with prediction of SBI test results using a one-dimensional thermal flame spread model. The author performed most of the SBI tests described, carried out the calculations, and wrote the paper. She analysed the results in cooperation with Prof. M. A. Kokkala who supervised the work. Paper II describes an alternative method for predicting SBI test results. The author is solely responsible for the study.

In Paper III, fire classification systems of surface linings in Japan and Europe are compared. The author compiled, analysed and interpreted the information on the classification systems during her STA Fellowship in Japan 1999–2000. She wrote the paper after her return to Finland. Dr Y. Hayashi participated in the study as an expert on the Japanese fire classification system.

Paper IV summarises the results of the SAFIR (Smoke Gas Analysis by Fourier Transform Infrared Spectroscopy) project, carried out in 1997–1999 within the European Standards, Measurement and Testing programme under Contract No. SMT4-CT96-2136. The work was performed in cooperation with 10 research institutes coordinated by VTT. The author participated in planning the project. She was responsible for all experiments and spectral analyses performed at VTT. In the interlaboratory trial (WP5), she acted as the work package leader planning and coordinating the work and performing the statistical analyses and result interpretations. She participated in writing the paper for WP1, WP4 and WP5. Finally, she compiled the paper on the basis of texts written by the project partners.

The experimental work on wooden facades and timber construction compartments reported in Papers V and VI was performed by a team of researchers and technicians. The author was responsible for data acquisition and analysis. She interpreted the results and drew the conclusions with Mrs T. Oksanen for Paper V and by herself for Paper VI. The author wrote Papers V and VI.

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Papers I–VI

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List of acronyms and symbols

A	area
BSL	Building Standard Law (of Japan)
CEN	European Committee for Standardization
CFD	computational fluid dynamics
EU	European Union
FIGRA	fire growth rate (index)
FO	flashover
FR	fire retardant
FTIR	Fourier transform infrared
g	gravitational acceleration constant
H	height of window opening
HRR	heat release rate
I_{ig}	ignitability index
INLR	implicit non-linear latent variable regression
I_Q	rate of heat release index
IR	infrared
ISO	International Organization for Standardization
k	coverage factor
k_f	coefficient of flame height correlation

LFS	lateral flame spread
m	exponent for calculating rate of heat release index
n	exponent of flame height correlation
O	opening factor
PMMA	polymethyl methacrylate
PTFE	polytetrafluoroethene
$\dot{q}''$	heat release rate per unit area (in kW/m^2)
$\dot{Q}$	heat release rate (in kW)
QTFA	quantitative target factor analysis
r	repeatability limit
R	reproducibility limit
SBI	single burning item
SMOGRA	smoke growth rate (index)
s_r/m	relative repeatability standard deviation
s_R/m	relative reproducibility standard deviation
SS	subsystem
t	time
THR	total heat release
TSP	total smoke production
V	flame spread velocity

w	width of pyrolysis area
WP	work package
x	height or vertical position
ρ	density

Subscripts

0	initial
ave	average
b	burner
ch	characteristic
f	flame
F	fuel
ig	ignition
mat	material
max	maximum
p	pyrolysis
RC	Room/Corner (test)
t	total
W	window

1. Introduction

The general goal of fire safety regulations is to provide life safety and sufficient protection to property in case of fire. To achieve this goal, requirements for structures, building materials, evacuation arrangements, and relative locations of buildings are set to define how buildings should be designed and constructed for their respective use. The requirements are related to prevention of ignition and fire spread, limitation of fire growth, evacuation provision, load-bearing capacity of structures, and prevention of spread of fire between buildings.

Traditionally, fire testing and classification systems are developed individually in different countries, each with its different background and circumstances. A wide variety of requirements has thus been drawn up. However, as a result of the development of transportation facilities and international trade, the harmonization of standards and fire classification systems has become an issue of increasing importance.

Fire classification systems, and building codes in general, can be divided into prescriptive and performance-based codes on the basis of the formulation of the requirements. The current trend of fire safety regulations is to proceed from prescriptive criteria towards performance-based approaches. However, prescriptive requirements will remain as an acceptable option for verifying fire safety, and the importance of fire testing will not decrease as a result of the development of performance-based fire codes.

In the European Union (EU), the development of the Euroclass system is approaching its completion after work of roughly ten years. The Commission Decision 94/611/EC implementing Article 20 of Directive 89/106/EEC on construction products [1] in the field of fire safety set in place the background to the harmonization process. The decision on the classification of the reaction-to-fire performance of construction products was published in February 2000 [2]. The Euroclass decisions include a classification system for construction products and define the test methods according to which the classification is determined. The Euroclass system requires that the member countries of the EU include the test methods and the classification in their legislation. The required fire performance for various purposes of use of construction products will still be decided nationally, but the requirements will be expressed in terms of harmonized standards.

The European classes of reaction-to-fire performance for construction products excluding floorings are based on four fire test methods: the non-combustibility test prEN ISO 1182 [3], the gross calorific potential test prEN ISO 1716 [4], the single burning item (SBI) test prEN 13823 [5], and the ignitability test prEN ISO 11925-2 [6]. The same test methods, excluding the SBI test, are used for floorings with the addition of the radiant panel test prEN ISO 9239-1 [7]. The details of specimen conditioning and substrate selection are given in EN 13238 [8], and the classification procedure is described in prEN 13501-1 [9].

Structural design rules, including fire design, are provided in Structural Eurocodes for the use of the member countries of the EU. The objective of the Eurocode programme initiated by the Commission of the European Community is to establish a set of harmonized technical rules for the design of building and civil engineering works. These rules would at first serve as an alternative to the national rules in force in the member states and ultimately replace them [10].

In Japan, the fire safety regulations are included in the Building Standard Law (BSL) consisting of General Provisions, Building Codes and Zoning Codes [11]. After its establishment in 1950, the BSL has undergone several revisions. Concerning fire safety, the latest reform emphasized the introduction of internationally accepted fire test methods and the possibility of performance-based fire regulations. The law to amend the BSL was issued in June 1998. The Enforcement Order and Notifications defining the details of the new fire classification system went into effect in June 2000. In the new Japanese fire classification system, the main test method is the cone calorimeter test ISO 5660-1 [12], applicable to all classes of so-called fire preventive materials.

The forthcoming European fire classification system does not include requirements for the combustion toxicity of construction products. However, the combustion toxicity and environmental aspects of industrial products are currently of growing interest and concern. The questions of which fire products, and in what concentrations, are emitted from building materials when they burn are increasingly important. There is also an increasing need for regulatory requirements.

The ISO Technical Report 13387-1 [13] divides the process of fire safety design into five subsystems (SS): SS1 – Initiation and development of fire and generation of fire effluents, SS2 – Movement of fire effluents, SS3 – Structural response and fire spread beyond the enclosure of origin, SS4 – Detection, activation and suppression, and SS5 – Life safety: occupant behaviour, location and condition.

The studies presented in this thesis discuss various aspects of fire safety assessment of construction products related mainly to SS1, but with some connection to SS3. Papers I and II deal with the prediction of results of the SBI test, the most important European reaction-to-fire test method for construction products exhibiting non-negligible contribution to fire. Paper III compares the forthcoming Euroclass system to the recently reformed fire classification system of Japan. Paper IV discusses an issue not covered by the Euroclass system: combustion toxicity of construction products. A method for determining toxic components of smoke gases is presented in Paper IV. Paper V deals with fire safety assessment of wooden facades for which the prescriptive requirements based on reaction-to-fire classes may be too restrictive or difficult to apply in some cases. The use of materials in facades can be regulated on the basis of the Euroclass system, but additional fire safety features of facades including combustible materials are also discussed in Paper V. Paper VI discusses gas temperature development and charring behaviour of timber construction compartments, related to structural fire design guided by the Eurocodes.

2. Literature review

Previous research related to the studies presented in this thesis is briefly introduced in this chapter. The reviews of various topics are non-exhaustive, concentrating on the work most relevant to Papers I–VI.

2.1 Flame spread and fire growth models

Spread of flame over the surface of a solid, combustible material is an important issue in fire safety because it influences the initial development of fire and the rate of heat release. In a room fire, the first item ignited is typically a single object. If the burning object is close to a wall covered with a combustible material, the wall lining may ignite and spread the fire. In this case, upward flame spread is especially significant due to its rapidity on a vertical surface.

Flame spread and fire growth models were extensively studied during the 1980’s and 1990’s. For instance, the EUREFIC research programme provided valuable information on evaluation of surface linings [14].

The models describing flame spread and fire growth are of varying complexity, ranging from simple empirical correlations to approaches solving the basic conservation equations for the gas-phase and solid-phase chemistry. The following review concentrates on models that take into account only the spread of the pyrolysis region over the surface of a material, focusing mainly on the concurrent upward flame spread. Models relating the heat release rate to a detailed description of in-depth solid-phase processes are not discussed here.

The starting point for several simple upward flame spread models is the one-dimensional differential equation [15]

$$V_p = \frac{dx_p}{dt} = \frac{x_f - x_p}{t_{ig,ch}} \qquad (1)$$

where x_p is the position of the pyrolysis front, x_f the flame height, and $t_{ig,ch}$ a characteristic ignition time. These quantities can be approximated with varying degrees of sophistication, permitting prediction of the flame spread velocity V_p.

Wickström and Göransson [16] have developed a simple model for predicting the heat release rate in ISO 9705 Room/Corner tests [17] on the basis of cone calorimeter data. In their model, the growth of the burning area is expressed as t and t^2 growth curves, governed by the inverse of the ignition time. The heat release rate of the lining is obtained as the sum of the contributions of the ignited parts at various times. The criterion for flame spread away from the vicinity of the burner is based on an assumed surface temperature. This prediction procedure for the heat release rate is known as the "Cone tools" model.

Qian and Saito have introduced an empirical model for upward flame spread, based on experimental flame spread characteristics and heat transfer mechanisms of corner fires [18]. They correlated the pyrolysis height and flame height to time, and the flame heat flux to height and time, by power law relations. The empirical correlations lack a fundamental basis, and are therefore valid only in the range of experimental conditions used in the derivation. The model was applied to prediction of flame spread on PMMA. Good agreement was found in the early part of the tests, but in later parts the prediction got worse due to the failure of the semi-infinite solid assumption used in the heat transfer equation.

The flame height can be expressed in terms of heat release rate as a flame height correlation:

$$x_f = k_f \left[\dot{Q}(t)\right]^n \tag{2}$$

where $\dot{Q}(t)$ is the heat release rate (including the contributions of the burner and the material), and k_f and n are experimentally determined constants, specific to the test method. Following the derivation presented by Saito, Quintiere and Williams [15], the flame front position can be expanded from Equation (2) as:

$$x_f = k_f \left[\dot{Q}_b(t) + x_{p0} w \dot{q}''(t) + \int_0^t w \dot{q}''(t-\tau) V_p(\tau) d\tau \right]^n \tag{3}$$

where $\dot{Q}_b(t)$ is the heat release rate of the burner, x_{p0} and w are the initial height and assumed constant width of the pyrolysis area, respectively, and $\dot{q}''(t)$ is the heat release rate of the material per unit area. The position of the pyrolysis front can also be expressed using the velocity:

$$x_p(t) = x_{p0} + \int_0^t V_p(\tau) d\tau \tag{4}$$

The resulting expression for the velocity of the pyrolysis front is:

$$V_p = \frac{1}{t_{ig}} \left\{ k_f \left[\dot{Q}_b(t) + x_{p0} w \dot{q}''(t) + \int_0^t w \dot{q}''(t-\tau) V_p(\tau) d\tau \right]^n - \left[x_{p0} + \int_0^t V_p(\tau) d\tau \right] \right\} \tag{5}$$

This is a Volterra type integral equation, where the unknown variable appears on both sides. In general, it can be solved using numerical methods. Analytical solutions can be found if the flame height is assumed to depend linearly on the heat release rate and if the heat release rate of the material can be expressed using simple mathematical correlations [19, 20].

The fire growth model for surface linings developed by Karlsson [21, 22] is based on Equation (5). He formulated two mathematical models: Model A for lining materials attached to walls and ceiling, and Model B for linings covering the walls only. Submodels for ignition by the burner, hot gas temperatures, surface temperatures, concurrent flow flame spread and heat release rate were included in both cases. In addition, downward flame spread was calculated in Model B. The flame spread velocity was solved using Laplace transforms. The limits of propagation and non-propagation for concurrent flow flame spread were determined from the expressions obtained for the roots [19]. A graphical representation of the limiting behaviour has been given by Baroudi and Kokkala [20].

Kokkala et al. have introduced a thermal model for upward flame spread from the same starting point as Karlsson, but instead of solving Equation (5) the flame spread is determined by finding $x_p(t)$ in the initial value problem [23]:

$$\frac{dx_p(t)}{dt} = \frac{x_f(t) - x_p(t)}{t_{ig}}, \qquad t > 0 \tag{6}$$

$$x_p(0) = x_{p0}, \qquad t = 0$$

$$x_f(t) = k_f\left[\dot{Q}(t)\right]^n, \qquad t > 0,\ n > 0,\ k_f > 0$$

The ignition time and heat release rate of the material are obtained from cone calorimeter tests. This model has been applied also to the prediction of SBI test results as presented in Paper I.

Quintiere has developed a comprehensive mathematical model simulating the ignition, flame spread, burn-out, and burning rate of wall and ceiling materials in a room [24, 25]. In his approach, thermal feedback from the room is accounted for by means of global computation of the wall surface temperature, the upper layer temperature and the heat release rate of linings. The governing equations are solved numerically.

Hasemi has developed a model for upward flame spread on a vertical combustible surface based on the concept of ignition and flame spread as a result of inert heating of the solid to an ignition temperature. The first formulation of the model dealt with a steady-state solution of the flame spread equation, making no difference between initial and asymptotic conditions [26]. The unsteady-state solution was added to a later version on the basis of an experimental relationship according to which the time difference between the arrivals of flametips and pyrolysis front to a certain height is approximately constant [27].

The computer model of upward flame spread by Beyler et al. [28] is based on sub-models of 1) ignition, 2) material heating, pyrolysis and burning rate, 3) flame spread and 4) flame and surface heat transfer. The flame spread on a vertical surface is calculated by breaking up the surface into a large number of elements whose conditions are independently computed. The heat release rate and the heights of the pyrolysis region, the flame and the burnout region are calculated by summing the contributions of the elements.

If a model is capable of predicting the distribution of surface temperature on a combustible material, the onset of pyrolysis and the ignition can be obtained on the basis of pyrolysis and ignition temperatures. This provides a completely general method for the prediction of flame spread, without restrictions of flame spread direction. Models based on computational fluid dynamics (CFD) predict the surface temperature by calculating heat transfer to solid boundaries.

Opstad has developed an algorithm for thermal flame spread on solid surfaces using cone calorimeter data combined with a CFD model [29]. The gas-phase modelling includes the k-ε model of turbulence, the eddy dissipation concept for combustion, a soot generation model, and the discrete transfer model for radiative heat transfer. The convective heat transfer to the walls is calculated using a logarithmic law. The surface temperature, used as the ignition criterion, is obtained by solving the one-dimensional heat conduction equation in the solid phase. The thermal properties of the lining material are derived from cone calorimeter data.

The fire growth model developed by Yan and Holmstedt [30] is based on the same principle as Opstad's model. However, they present two methods to describe the reaction of the combustible material when solving the heat conduction equation: 1) the use of small-scale test data as input to describe the burning of the solid fuel, and 2) the development of a pyrolysis model to describe the pyrolysis and charring of the solid fuel. The second approach increases the generality of the model by introducing in-depth pyrolysis effects.

Different flame spread models have recently been introduced to the SOFIE (Simulation of Fires in Enclosures) CFD model [31] developed by a consortium of several European fire research laboratories coordinated by Cranfield University. These approaches are based on an empirically determined heat of gasification, the heat release rate for a material obtained from cone calorimeter tests [32] or the description of solid pyrolysis [32, 33].

Thermal flame spread models are generally limited to a specific test arrangement or fire scenario. Therefore, the use of CFD models in fire growth modelling is expected to increase due to their wider applicability to different geometries and scenarios.

2.2 Flammability indices

The fire classification of products is traditionally based on performance indices, which are characteristic parameters derived from the results of fire tests. Efforts have been made to define physically based flammability indices that correlate with the fire hazard of specific products.

Babrauskas has devised a procedure for estimating the full-scale heat release rate of wall linings on the basis of cone calorimeter test results. He found that the time to flashover in a room is directly proportional to the maximum heat release rate per unit area divided by the time to ignition obtained from cone calorimeter tests [34].

Another approach to predicting the time to flashover on the basis of cone calorimeter data was introduced by Östman and Nussbaum. According to their empirical relation, the time to flashover can be calculated using the time to ignition multiplied by the square root of the density of the lining and divided by the total heat release during the peak period of a cone calorimeter test [35]. In a later study, the time to flashover was predicted by a power law of the ignition time, the density and the total heat release calculated over 300 s after ignition [36].

Dillon et al. [37] have developed a parameter indicating whether flashover is likely to occur in a Room/Corner test. The parameter is calculated on the basis of heat release rate and time to ignition data from cone calorimeter tests. They also present a method to estimate the peak heat release rate and total smoke released, if flashover does not occur. In addition to wall linings, the methods have been applied to the prediction of heat and smoke release in a full-scale cable tray fire test [38].

Delichatsios and Saito have discussed key flammability properties of charring and non-charring materials [39], used as input for simulating upward fire spread and growth [40]. Among these parameters they introduced a material flammability number related to the ratio of the flame height to the pyrolysis length. The material flammability number is calculated as a function of the heat of combustion, the effective heat of gasification and the radiative fraction of the heat release rate.

Shields et al. formulated a procedure for analysing ignition data obtained from cone calorimeter tests on the basis of a flux time product, which is the product of the effective heat flux raised to a power and the time to ignition. They used the procedure for determining critical heat fluxes and changes in the convective heat loss related to different specimen orientations and modes of ignition [41].

Tewarson identified a number of flammability parameters to be used for assessing fire hazards and fire protection requirements. The parameters presented were the critical heat flux and the thermal response parameter associated with ignition, and the heat release parameter and the fire propagation index related to combustion and fire propagation, respectively. He also discussed how these parameters could be determined by means of various fire test apparatus [42].

Kokkala, Thomas and Karlsson [43] have introduced rate of heat release and ignitability indices for predicting the performance of surface linings in the ISO 9705 Room/Corner test on the basis of cone calorimeter test results. The physical basis of their approach was established by employing dimensional analysis to find the key parameters of fire growth in a room. The independent variables were identified and the corresponding dimensionless variables were derived. Considering the characteristic features of the fire scenario, the rate of heat release and ignitability indices were defined from the results of a theoretical analysis of fire growth by a dimensionless power law approximation.

2.3 Modelling of SBI test results

Due to the short history of the SBI test in its current form, only a limited number of models for predicting SBI test results has been introduced so far. The objective of the models is to predict the heat release rate of a specimen in the SBI test, in order to calculate a fire growth rate index, FIGRA, that is the main classification quantity to determine the Euroclass of the product. The calculation of FIGRA from heat release rate data is explained in Section 3.3.

The first modelling approach on the SBI test was presented by Messerschmidt, van Hees and Wickström [44]. The basic assumptions made in the procedure for modelling the heat release rate in the SBI test by means of cone calorimeter data are the same as in the Cone tools model [16] developed for predicting the Room/Corner test behaviour of surface linings: 1) the burning area growth rate and the heat release rate are decoupled, 2) the burning area growth rate is proportional to the inverse of the time to ignition on the small scale, and 3) the history of the heat release rate per unit area at each location in the predicted test is to be the same as on the small scale. The area growth rate is described by the empirical function

$$A(t) = A_{\max} \cdot \left[1 - \left(1 + \frac{t - t_{ig}/2}{t_{ig}} \right) \cdot \exp\left(-\frac{t - t_{ig}/2}{t_{ig}} \right) \right] \tag{7}$$

where $A_{\max}$ is the maximum area involved and t_{ig} is the time to ignition in the cone calorimeter test. The flame spread can follow two different routes with different $A_{\max}$ values. Initially, all products are assumed to obey the same area growth function, but, if the sustained flame height reaches the upper edge of the specimen, $A_{\max}$ changes. The criterion for selecting the flame spread route is expressed in terms of the combined heat release rate of the burner and the specimen. The heat release rate of the specimen material is calculated as

$$\dot{Q}_{mat} = \sum_{i=1}^{N} \Delta A_i \cdot \dot{q}''_{N-i} \tag{8}$$

where ΔA_i is the incremental burning area growth at the time increment i, and $\dot{q}''_{N-i}$ is the heat release rate per unit area in the cone calorimeter test after (N-i) time increments. The model predicts the first part of the heat release rate curve and the FIGRA value with good or reasonable agreement for most products. However, failure of the prediction has been observed for melting materials and products with an extensive lateral flame spread or heavy deformation.

Hansen has developed further the model of Messerschmidt et al. by introducing three different flame spread routes. The selection of the route for a product is made using multivariate statistical analysis [45]. The modification improves the ability of the model to predict the development of heat release rate in later phases of the test after the first maximum, especially for products showing significant lateral flame spread. However, some problematic product types still remain. Hansen and Hovde have also applied the improved model to the prediction of smoke production in the SBI test with promising preliminary results [46].

North et al. have applied Karlsson's thermal flame spread model [21] to develop engineering tools for the prediction of flame spread in different full-scale and intermediate-scale fire test scenarios, including the SBI test. Cone calorimeter data, the density of the specimen and characteristic parameters of the test arrangement are needed as input. In addition, four tuning variables have been introduced to optimise the model for the specific scenario by sensitivity analysis. The flame spread equation can be solved either numerically by using input data directly from the cone calorimeter or analytically by representing the data as a mathematical expression [47]. The analytical approach predicts the heat release rate in the SBI test relatively well, but the numerical solution tends to overestimate the development of heat release. The Euroclass predictions of the analytical model were successful for about 60 % of the products studied.

A method of predicting the heat release rate in the SBI test is introduced in Paper I. The procedure employs a one-dimensional thermal flame spread model [23], with input parameters selected on the basis of the SBI test characteristics and model tuning. The details of the model development and performance are presented in Paper I.

The index approach suggested by Kokkala et al. [43] is applied to predicting SBI test performance in Paper II. The basic fire growth processes in the initial stages of the SBI and Room/Corner tests are similar. In later stages, however, the situation changes due to the different specimen configurations. The dimensionless variables needed to describe the SBI test are a subset of those for the Room/Corner test and can be derived by ignoring the height of the room and the dimensions of the opening. The rate of heat release and ignitability indices provide a simple means with which to estimate the classification of a product in the forthcoming Euroclass system as presented in Paper II. The model gives only FIGRA and Euroclass estimates, not predictions of the heat release rate as a function of time or the total heat release.

The common feature of the prediction methods for SBI test results described above is that they are empirically based mathematical models including several approximations and simplifications. Their main advantage is that only one cone calorimeter test at a single exposure level is needed as input. However, various product groups have been found problematic for these models and require further examination. Depending on the model used, the problematic product groups include materials that are fire-retarded, melting or highly combustible, have a reflective coating, or exhibit extensive lateral flame spread or heavy deformation.

2.4 Determination of toxic gases

The majority of fatalities in fires can be attributed to inhalation of toxic gases. The combustion toxicity of industrial products is therefore an issue of interest and concern. Even though the combustion toxicity evaluation is not required in the Euroclass system, the questions of which compounds, and in what concentrations, are emitted from burning construction products are increasingly important.

Considering the generation of chemical compounds in fires it must be noted that some toxic species are material-dependent, whereas others are dependent on the conditions of the fire itself. Since combustion is an oxidation process, it results in transformation of organic species to some oxidised state, the extent of oxidation depending on ventilation conditions [48]. Tewarson has discussed the species generation in detail, and has provided quantitative data on the yields of various species [49].

The determination of toxic components in hot smoke gases is not straightforward. Due to the different properties of various gas components, a different time-consuming measurement procedure for each species has traditionally been used. Moreover, measuring the concentration as a function of time during a fire test is impossible in the case of certain methods giving only the average concentration over the entire measurement period. Different methods for analysing fire effluents are outlined in the ISO CD 19701 document. The advantages and limitations of the various techniques are also described [50].

The use of FTIR spectrometers overcomes many of the problems of smoke gas analysis. FTIR spectrometry provides a continuous monitoring technique simultaneously for all gas components showing a characteristic spectral band in the infrared region of the spectrum. A Nordic standard method of measuring smoke gas concentrations by the FTIR technique [51] was published in 1993. The SAFIR project, described in Paper IV, has provided new information on the recommendable sampling and analysis techniques and the precision of the method.

The FTIR method has been applied to smoke gas analysis of, for example, rubber, plastics [52], chemicals, polymers [53, 54], textiles [55] and furniture materials [56]. The most recent studies of determining toxic species in fire gases by the FTIR spectrometry have been published by Blomqvist et al. and by Simonson et al.; the former relates to TV sets [57], while the latter concerns building and furnishing materials [58].

Future challenges of smoke gas analysis, including the FTIR technique, are related to the environmental effects of fires. Combustion toxicity data are needed as input for models to assess the safety and well being of humans and the environment.

2.5 Facades

Several research groups from different countries have studied fire safety aspects of facades and exterior wall claddings. Wade and Clampett have recently produced a comprehensive review of fire tests and requirements for exterior claddings [59].

Facade testing has long traditions in Sweden. In 1958, Johannesson and Larsson carried out full-scale and laboratory-scale fire tests to examine the possible extent and methods for the use of combustible materials in non-load-bearing external walls in fireproof buildings. The results emphasised the importance of material selection and structural design in the fire safety of buildings of varying heights [60].

Ondrus and Pettersson have performed fire tests on several types of external additional insulation systems applied to facades of multi-storey buildings. The purpose of the test series was to study the increased risk of fire spread along the facade and through the windows in the storeys above the fire room. As a result, acceptance criteria for external claddings were formulated [61]. At present, these criteria are applied to test results according to SP FIRE 105, the Swedish standard fire test of facades [62].

In Canada, McGuire studied the vertical flame spread characteristics of exterior cladding materials in the 1960’s. He observed two different types of facade behaviour: either the cladding material decisively propagated fire upwards shortly after ignition, or it made little contribution to the flames of the ignition source [63].

Harmathy has discussed several design solutions related to fire safety. Concerning facades, he suggested flame deflectors for preventing the spread of a compartment fire to other apartments of the building. Flame deflectors are light metal panels mounted above windows and held in a vertical position by a fusible fastening device. In the case of fire, flame deflectors fall down to a horizontal position when activated by flames emerging from the window below. Harmathy’s results revealed the importance of sufficient depth (at least 1 m) and width (at least window width + 1.2 m) of the deflector in effective fire protection [64].

Oleszkiewicz has studied the heat transfer from a window fire plume to a facade. He recognised three important factors influencing the level of thermal exposure to the exterior wall: the heat release rate of the fire, the window dimensions, and the facade geometry [65]. In a series of full-scale tests by Oleszkiewicz, a horizontal projection above a window was found to offer substantial protection to the wall above the window, whereas an impractical height of a spandrel wall was required to be equally effective [66].

Rogowski et al. have performed large-scale tests on various external wall insulation systems in UK. External and internal fire spread and the extent of damage were compared. Based on the test series, design recommendations for various cladding types were given to reduce the risk of vertical fire spread [67].

In Japan, Hokugo et al. have studied the upward fire spread through balconies. Four mechanisms of vertical fire spread were reported: exposure of the balcony fence to the external flame from lower storeys, heating and ignition of combustible materials on the balcony by the external flame, heating and ignition of the inner surface of the balcony fence by burning objects on the balcony, and further fire development to the upper storeys [68].

Another balcony study from Japan, by Suzuki et al., deals with the effects of the balcony depth on the flames ejected from the opening of the fire room. Tests were performed using a 1/7-scale model of a seven-storey building. It was found that the shape of the external flame is determined by the depth of the balcony, excluding the horizontal length from the edge of the balcony to the top of the ejected flame that is independent of the balcony depth [69].

Klopovic and Turan have recently reported the results of an Australian test series investigating the likelihood of external fire spread in the case of a non-combustible facade. In the first part of the study, the effects of ventilation conditions on the fire plume were examined with particular consideration being given to repeatability. To evaluate the repeatability, the internal ventilation conditions were grouped into through draft and no-through draft cases, and the data were averaged over a consistent external flaming period and then non-dimensionalised [70]. In the second part, the predicted and experimental plume characteristics were compared. Glass breakage times and heat transfer from the external plume were also examined [71].

In Finland, the fire research of upward flame spread and facades has concentrated mostly on wood products [72, 73]. The intermediate-scale test arrangements of these test series performed at VTT were the basis of the first version of the intermediate-scale standard facade test ISO/FDIS 13785-1 [74], even though the test method has undergone several modifications during the standardisation process.

Development of international standards of intermediate-scale [74] and full-scale [75] tests for facades is in progress in the ISO. Since these draft standards do not include acceptance criteria, the evaluation principles and requirements must be defined by the approving authority. Basic principles of criteria adaptable to various facade test arrangements are proposed in Paper V.

On the European level, a fire test for facades and curtain walling systems is under development in CEN TC127. As a part of this activity, different types of risks related to facades have been studied by van Hees. An overview of the situation in different European countries with respect to facade testing has also been given [76].

A current research topic in the field of fire safety of facades is the effect of structural details on fire spread. For example, possibilities of preventing fire spread by different protrusions need further examination.

2.6 Gas temperatures in compartment fires

The history of research into compartment fires dates back to the 1920's when Ingberg performed the seminal full-scale fire tests in the USA [77]. The goal of his work was to examine the question of whether the severity of standard test fires had any relation to real fire conditions in buildings. Ingberg's experiments laid the foundation for the concept of fire resistant compartmentation.

The first systematic study of the behaviour of fully developed fires was carried out in Japan 1949–1957 including 14 full-scale fire experiments of compartments of different sizes and window areas. The results were reported by Kawagoe, concluding that the burning rate of fuel depends on the size and shape of the ventilation opening of the compartment [78].

A few years later, Kawagoe and Sekine [79] presented a method for predicting the temperature-time curve of a compartment fire on the basis of energy balance

$$\dot{Q}_C = \dot{Q}_L + \dot{Q}_W + \dot{Q}_R + \dot{Q}_B \qquad (9)$$

where $\dot{Q}_C$ is the rate of heat release due to combustion, and $\dot{Q}_L$, $\dot{Q}_W$ and $\dot{Q}_R$ are the rates of heat lost by convection due to replacement of hot gases by cold gases, by conduction to compartment boundaries and by radiation through openings, respectively. Kawagoe and Sekine did not include the term $\dot{Q}_B$, the rate of heat storage in the gas volume. In fact, it can usually be neglected since it is significant only in the case of very fast temperature rise (i.e. at flashover) in a compartment of a large volume.

An important parameter introduced in these two Japanese studies is the ventilation factor $A_W H^{1/2}$ where A_W and H are the area and height of the window opening of the compartment, respectively. The burning rate of the fire load consisting of wooden cribs was found to be directly proportional to $A_W H^{1/2}$. Kawagoe's deduction of the ventilation factor can be considered semi-empirical, but it is also derivable by theoretical analysis of the flow of gases in and out of the burning compartment [80, pp. 325–334]. The following assumptions must be made:

- The gases in the compartment behave as if they are "well stirred"; i.e. their properties are uniform throughout the volume.
- There is no net flow created by buoyancy within the compartment.
- Hot gases leave the compartment above a neutral plane and cold air enters below it.
- The flow of gases in and out of the compartment is driven by buoyancy forces.
- There is no interaction between the inflowing and outflowing gases.

Information on the size and shape of the ventilation opening is commonly used in the calculation of parametric temperature-time curves by various methods, often in the form of the opening factor O defined as follows:

$$O = \frac{A_W H^{1/2}}{A_t} \tag{10}$$

where A_t is the total area of the boundary surfaces of the compartment including the window opening.

Several experimental and theoretical studies were carried out in the late 1960's and in the 1970's to develop design methods for structural elements. Magnusson and Thelandersson developed a computer model for solving the energy balance equation, making the following assumptions [81]:

- The energy release rate is ventilation controlled during the fully developed stage of the fire, but based on data from full-scale experiments during the fire growth and decay stages.
- Combustion is complete and takes place entirely within the confines of the enclosure.
- The temperature inside the enclosure is uniform at all times.
- A single surface heat transfer coefficient is used for the entire surface of the enclosure.
- The heat flow to and through the enclosure boundaries is one-dimensional and the boundaries are assumed to be "infinite slabs".

The same assumptions have been made in several other models solving the energy balance equation. The temperature-time curves calculated using the model by Magnusson and Thelandersson have been presented systematically for various fire compartment types representing different boundary material properties as sets of curves corresponding to several fire load densities and opening factors [82]. These curves have become a frequently used basis for the design of structural elements.

In the models described above, combustion is assumed to be ventilation controlled throughout the fully developed stage of the fire. Harmathy analysed data from a large number of wooden crib fires in compartments and identified a transition point between ventilation-controlled and fuel-controlled fires [83]. He has suggested the following distinction for fires involving cellulosic fuels:

Ventilation control:
$$\frac{\rho g^{1/2} A_W H^{1/2}}{A_F} < 0.235 \qquad (11)$$

Fuel control:
$$\frac{\rho g^{1/2} A_W H^{1/2}}{A_F} > 0.290$$

where ρ is the density of air, g the gravitational acceleration constant, and A_F the surface area of the fuel. The transition between these regimes is ill defined.

Babrauskas and Williamson have developed a computer model that includes a means to determine whether the fire is ventilation-controlled or fuel-controlled, provided that the rate of pyrolysis of the fuel is known at all times. The description of the compartment and the fuel are required as input [84, 85]. Babrauskas has also introduced a hand calculation method where the gas temperature of a post-flashover fire is expressed as a product of factors relating to burning rate stoichiometry, wall losses, opening height and combustion efficiency [86].

Another relatively simple approach for predicting the temperature-time development of a compartment fire has been introduced by Lie [87, 88]. His basic idea was that if the objective is to develop a method of fire resistance design, it is sufficient to find a temperature-time curve that with reasonable likelihood will not be exceeded during the lifetime of the building. Thus, he developed analytical expressions of characteristic temperature-time curves as functions of the opening factor and the duration of the fire (determined by the fire load and the opening factor). For the fully developed period, the derivation of the curves was based on the method of Kawagoe and Sekine [79]. The equation for the decay period of the fire was defined bearing in mind that a longer duration of the fully developed fire leads to a slower decrease of the temperature.

The theory of a simplified parametric approach to post-flashover fires was proposed by Wickström [89]. In his model, the net heat flux to the enclosure walls is calculated by convolution between a step function dependent on the thermal inertia of the boundaries and the temperature rise of the fire. By introducing a modified time, a closed-form approximate solution for the gas temperature in the compartment is obtained. Wickström's method is the basis for the parametric temperature-time curves given in the Eurocode 1 [10].

Franssen has suggested improvements on the Eurocode 1 method for calculating temperature-time curves [90]. The proposed modifications related to properties of multi-layer walls, fuel-controlled fires and ventilation during the heating phase have been introduced to the draft for the revised Eurocode 1 [91].

A number of test series of fully developed fires in large compartments has been performed. For example, Hagen and Haksever have reported tests carried out using a fire room made of aerated concrete with inner dimensions of 14.4 m × 7.2 m × 3.5 m. The purpose of the test series was to investigate the influence of natural ventilation conditions and the distribution of the fire load on the development of the fire [92]. Kirby et al. have measured gas temperatures and temperatures of protected and unprotected steel beams and columns inside a concrete compartment of size 23 m × 6 m × 3 m. They examined the applicability of the equivalent time of fire severity given by Eurocode 1 to large compartments [93].

On a small scale, the influence of the enclosure shape and opening width on the burning rate has been studied by Thomas and Bennetts [94]. They concluded that for the same opening size, the mass loss rate in a wide enclosure is substantially higher than that in a long enclosure.

The development of fires in compartments of moderate size and made of inert materials is well understood today. Key issues in the current research are fires in large or long enclosures where the assumption of a uniform temperature is not valid, and the contribution of the combustible parts of the construction to the fire. The study presented in Paper VI is related to the latter. Comparable fire experiments have not been reported before.

2.7 Charring and fire resistance of timber

The fire endurance of a wood member or assembly depends on the performance of its protective membrane, the extent of charring of the structural wood elements, and the load-carrying capacity of the remaining uncharred portions of the structural wood elements. White has reviewed the analytical methods for determining these factors and discussed the major properties of wood affecting the thermal and structural response of timber assemblies [95]. Several aspects related to the prediction of the fire resistance of lightweight wood-framed assemblies have been reviewed recently by Bénichou and Sultan to aid the development of fire resistance models and design equations [96].

Several authors have developed models for the charring of wood. For instance, Mikkola has introduced a simplified analytical model and studied the dependence of the charring rate on the density and moisture content of wood, the external heat flux, and the oxygen concentration of the surrounding air [97, 98]. Quintiere has developed a semi-quantitative model for the burning rate of solid materials based on the conservation of mass and energy, including the char layer processes [99]. Lau et al. have reviewed empirical models for the charring of wood and developed a linear model for predicting the residual area of 2 × 4 timber exposed to constant-temperature or variable-temperature heat attacks. Their study includes an evaluation of the variability of charring rates [100].

A method for predicting the charring of protected wood studs in full-scale furnace wall tests on the basis of cone calorimeter data measured at 50 kW/m^2 has been developed by Tsantaridis and Östman [101]. In a study of the protective ability of different gypsum plasterboards it was found that the time to the onset of charring is predicted best by using board thickness as the prediction parameter, whereas the recommended prediction parameter for the charring rate is the weight per unit area of the boards [102]. The data of Tsantaridis and Östman [101] have been used also by Silcock and Shields for correlating local fire severity and char depth [103].

Fredlund has developed an analytical model for the heat and mass transfer in timber structures exposed to fire [104]. His model has been successfully applied to calculating the fire resistance of wood-based boards and timber wall constructions [105].

König et al. have reported a series of fire tests of timber frame assemblies exposed to standard and parametric fire curves [106]. The following protection and charring phases were identified: 1) a charring phase of initially unprotected timber, 2) a protection phase prior to the failure of the protective lining (complete or incomplete protection), and 3) a post-protection phase after the failure of the lining. The data have been used for developing a design model for solid timber frame members in floor and wall assemblies [107].

At Forintek in Canada, a computer model for predicting heat transfer through uninsulated wood-stud walls protected by gypsum plasterboard has been developed [108, 109, 110]. The model has been found suitable for fire safety engineering purposes.

3. Methods

In this chapter, the experimental methods and mathematical models used in the studies of Papers I–VI are introduced. The uncertainty of measurements and the sensitivity of models are also discussed.

The cornerstone of many reaction-to-fire test methods is the measurement of the heat release rate by using oxygen consumption calorimetry. Papers I–III discuss the comparison of two of these methods: the cone calorimeter and the SBI test. The cone calorimeter is the most acknowledged small-scale fire test method internationally. The SBI test will be the main classification test method in the European Union for products with a non-negligible contribution to fire.

FTIR spectrometry is a method for continuous monitoring of several toxic components of smoke gases simultaneously, as described in Paper IV.

The non-standard fire experiments of wooden facades and compartments, presented in Papers V and VI, are described in terms of test arrangements and measurements.

3.1 Oxygen consumption calorimetry

The most important parameter in fire safety engineering is heat release because it quantifies the size of fire. Efforts for finding methods to measure heat release rates from burning materials have been made since the early years of fire science.

The oxygen consumption principle was discovered in 1917 when Thornton showed that an approximately constant net amount of heat is released per unit mass of oxygen consumed in complete combustion for a large number of organic liquids and gases [111]. This finding was forgotten for several decades until Huggett rediscovered Thornton's study and showed that the same relationship is also valid for many synthetic polymers and solid natural fuels [112]. Thus, it is sufficient to measure the oxygen consumed in combustion in order to determine the net heat released.

The basic arrangement for heat release measurements by oxygen consumption calorimetry is that all combustion products are collected by a hood and removed through an exhaust duct. At a distance sufficient for adequate mixing of gases, the flow rate and the gas composition in the duct are measured. The minimum requirement is to measure the O_2 concentration, but the accuracy can be improved by adding instrumentation for CO_2, CO and H_2O measurements.

Equations to calculate the heat release rate in various applications are given by Parker [113]. It is noted, however, that the analysis is approximate. The following simplifications have been listed by Janssens [114]:

- The amount of energy released by complete combustion per unit mass of oxygen consumed is taken as a constant, generally 13.1 MJ/kg of O_2.
- All gases are assumed to behave as ideal gases, i.e. one mole of any gas occupies a constant volume at the same pressure and temperature.
- Incoming air consists of O_2, CO_2, CO, H_2O and N_2. All "inert" gases not participating in the combustion reactions are lumped into the nitrogen.
- O_2, CO_2 and CO are measured on a dry basis, i.e. water vapour is removed from the gas sample before gas analysis measurements are made.

At present, oxygen consumption calorimetry is an internationally accepted method of measurement and it is successfully used in bench-scale and full-scale fire experiments for materials and products, including several standard fire test methods.

3.2 Cone calorimeter

The cone calorimeter test ISO 5660-1 [12] is a bench-scale fire test method for assessing the contribution that the product tested can make to the rate of evolution of heat during its involvement in fire. The main parts of the apparatus are a cone-shaped radiant electrical heater with a temperature controller, a spark igniter, a weighing cell, a specimen holder, and an exhaust gas system. The development of the cone calorimeter [115] and its technical design features [116] have been described by Babrauskas. A schematic picture of the cone calorimeter is presented in Figure 1.

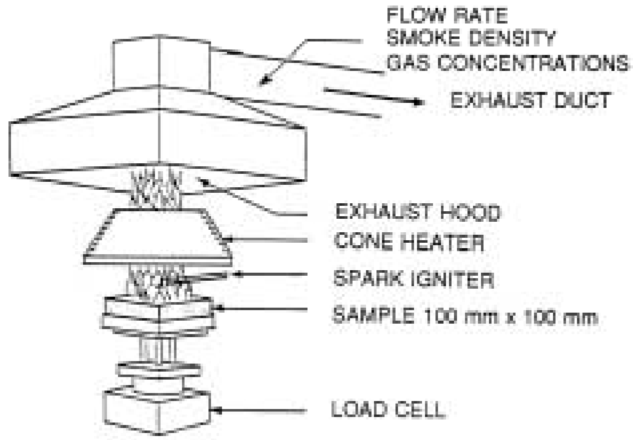

Figure 1. A schematic picture of the cone calorimeter.

The test specimen has an area of 100 mm × 100 mm and a maximum thickness of 50 mm. In a standard test, the specimen in the specimen holder is positioned under the cone-shaped heater on the weighing cell. The orientation of the specimen can be either horizontal or vertical, the horizontal orientation being more common in standard testing. The combustion products flow through the top opening of the heater into the hood and the exhaust duct from which a gas sample is taken for gas analysis. The main measurements of the test are the time to ignition, the mass loss, the heat release rate (based on oxygen consumption calorimetry), and the effective heat of combustion.

The highly uniform irradiance over the entire specimen surface and the possibility of measuring quantities per unit area and mass of the material tested make the cone calorimeter an excellent instrument for determining material parameters and for other scientific purposes. Naturally, the full-scale effects of products and structures cannot be revealed in cone calorimeter tests due to the small size of the specimen.

3.3 SBI test

The single burning item (SBI) test [5] is a new fire test method developed for the forthcoming Euroclass system by a group of European fire laboratories on the basis of the specifications defined by a group of European fire regulators. The development work included the design of a prototype, the installation of test facilities, the determination of the accuracy of the method and the production of data needed to finalize the classification system [117].

The SBI test is based on a fire scenario of a single burning item, for example a wastebasket, located in a corner between two walls covered with the surface lining to be tested. The SBI test apparatus is shown schematically in Figure 2.

The SBI test specimens are installed on a specimen holder consisting of two vertical wings made of non-combustible board. The specimen holder wings of sizes 1.0 m × 1.5 m and 0.5 m × 1.5 m form a right-angled corner configuration.

The thermal exposure on the specimen surface is produced by a triangle-shaped propane gas burner placed at the corner formed by the specimen wings. The heat output of the burner is 30 kW resulting in an average maximum heat exposure of about 40 kW/m^2 on an area of approximately 300 cm^2. The burner simulates a single burning item.

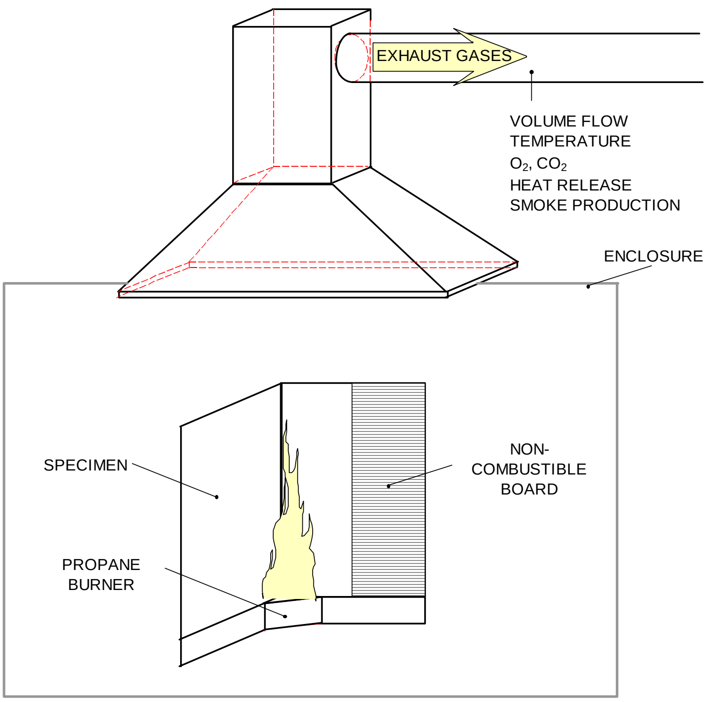

Figure 2. A schematic picture of the SBI test apparatus.

The SBI test is performed under a hood. The combustion gases are drawn to an exhaust duct equipped with sensors to measure the temperature, light attenuation, O_2 and CO_2 mole fractions and flow-induced pressure difference. The heat release is determined using oxygen consumption calorimetry. The smoke production is measured on the basis of the attenuation of light by combustion gases. In addition, lateral flame spread and the occurrence of flaming droplets or particles are visually observed.

The classification parameters of the SBI test are the fire growth rate index (FIGRA), the lateral flame spread (LFS), and the total heat release during the first 600 seconds of the test (THR_{600s}). Additional classification is defined for smoke production in terms of the smoke growth rate index (SMOGRA) and the total smoke production (TSP_{600s}), and for flaming droplets and particles according to their occurrence and burning time during the first 600 seconds of the test.

For determining FIGRA, the measured values of the heat release rate are divided by the corresponding times of measurement. FIGRA is the maximum value of this quotient. To prevent signal noise in the early part of the test from having a determining effect on the classification, FIGRA is calculated from smoothed data and threshold values of the heat release rate (HRR) and total heat release (THR) are used to initiate the calculation.

3.4 Models for predicting SBI test results

Since the development of the SBI test method, correlations between the cone calorimeter and SBI test results have been subject to increasing interest. The SBI test is relatively costly: for a single test, more than 2 m^2 of specimen material is needed, and the operating costs of the intermediate-scale test apparatus increase the price. The cone calorimeter is a well-established small-scale fire test method, requiring only a small piece (0.01 m^2) of specimen material. Thus, models predicting the results of SBI tests on the basis of cone calorimeter data provide economical tools for product development and quality control, even though the SBI test is required in the actual classification.

Two methods for predicting the SBI test results of a construction product on the basis of cone calorimeter data are presented in this thesis. Paper I introduces a prediction procedure for heat release rate curves from which FIGRA and Euroclass estimates can be determined. A regression equation for calculating FIGRA values to predict classification is presented in Paper II.

3.4.1 One-dimensional thermal flame spread model

The one-dimensional thermal flame spread model developed by Kokkala et al. for upward flame spread on wall linings [23] can be applied to the SBI test as shown in Paper I. The input data of the model are rate of heat release curves from cone calorimeter tests performed at the heat exposure level of 50 kW/m^2.

The starting point of the calculation is Equation (1), the one-dimensional differential equation describing upward flame spread. The flame spread is determined by solving the initial value problem of Equation (6) (see Section 2.1). The total heat release rate $\dot{Q}(t)$ is calculated as the sum of the contributions of the burner and the material. The heat release rate of the material is

$$\dot{Q}_{mat}(t) = x_{p0} w \dot{q}''(t) + w \int_{\tau=0}^{\tau=t} \dot{q}''(t-\tau) \frac{x_f(\tau) - x_p(\tau)}{t_{ig}} d\tau \qquad (12)$$

where w and x_{p0} are the width and initial height of the pyrolysis area, and $\dot{q}''(t)$ and t_{ig} are the heat release rate (HRR) curve and the ignition time from the cone calorimeter test, respectively.

The ignition time is determined from the HRR curve as the time when the heat release rate per unit area reaches 50 kW/m^2, which is in good agreement with visual observations. This method to determine the ignition time, however, is more objective than visual perception.

To apply the model to predicting SBI test results, the input parameters x_{p0}, w, k_f and n were determined and optimised by examining the features of the SBI test arrangement and based on model tuning. In addition, input data from cone calorimeter tests run at the exposure level of 50 kW/m^2 were scaled to lower levels selected on the basis of practical experience and model tuning.

The model was optimised using particle board as a tuning material (see Paper I for details). In the tuning, there were two aspects of major importance: the shape of the predicted HRR curve and the resulting FIGRA value determining the classification. It was found that reproducing the shape of the HRR curve throughout the whole SBI test is unrealistic with this model. However, the early stage of the test can be predicted well for several types of materials. In general, the height and shape of the first HRR peak in the SBI test determine the FIGRA value. The most interesting stage of the test is therefore its early part including the first major HRR peak. THR_{600s} is used as another heat release classification quantity, but FIGRA determines the class in most cases. Thus, successful modelling of the first peak of the SBI heat release rate curve is usually adequate to predict the classification of a building product correctly.

In many cases, the flame front spreads on the surface of an SBI test specimen both vertically and laterally. The one-dimensional model applied takes into account only the vertical direction, but the effect of the lateral flame spread can be compensated to some extent by the selection of the input parameters and the way of using the HRR curve from the cone calorimeter test. As a result of calculations according to Equations (6) and (12), the predicted heat release rate curves of SBI tests are obtained. From these curves, FIGRA values determining the product classification can be calculated.

3.4.2 Model based on rate of heat release and ignitability indices

An alternative and mathematically simpler approach to predict the results of an SBI test is presented in Paper II. In this method, FIGRA predictions are calculated from a regression equation on the basis of ignitability and rate of heat release indices (I_{ig} and I_Q, respectively) obtained from cone calorimeter data measured at the heat exposure level of 50 kW/m^2. The equations for the indices originally proposed by Kokkala et al. [43] are the following:

$$I_{ig} = 1/t_{ig} \tag{13}$$

$$I_Q = \int_{t_{ig}}^{t_{end}} \left[\frac{\dot{q}''(t)}{(t - t_{ig})^m} \right] dt \tag{14}$$

where t_{ig} is the time to ignition, t_{end} the end time of the test and m a constant. The denominator of the integrand represents a weighting function that gives a higher importance to the values of the heat release rate immediately after ignition than to those occurring later. Originally, the indices were developed for predicting the performance of surface linings in the ISO 9705 Room/Corner test. Since the basic fire growth processes in the initial stages of the tests are similar, the index approach can be applied to the prediction of SBI test results. Due to the different parameters to be predicted, however, the weighting of the HRR curve (i.e. the value of m) used as input is different.

In order to base the index approach to the SBI test on a wide range of ignition and heat release behaviour and on a sufficient amount of data, a series of over 200 artificial cone calorimeter data files for hypothetical products was generated. The shape of the HRR curve (see Figure 3 of Paper II) was assumed to be of the form

$$\dot{q}''(t) = \dot{q}''_{\max} (t / t_{\max}) \exp\left[-(t / t_{\max} - 1)\right] \tag{15}$$

where $\dot{q}''_{\max}$ is the peak value of the heat release rate per unit area occurring at time $t_{\max}$. This functional form was chosen because a wide range of products exhibits this curve shape in the initial part of the cone calorimeter test. Similarly to the one-dimensional thermal flame spread model, t_{ig} was determined as the time when the heat release rate per unit area reaches 50 kW/m^2. The selection of t_{ig} defines a time shift to the beginning of the HRR curve. The ranges for the parameters were 55–700 kW/m^2 for $\dot{q}''_{\max}$, 5–60 s for $t_{\max}$, and 5–60 s for t_{ig}, corresponding to the typical behaviour of construction products in cone calorimeter tests at an irradiance level of 50 kW/m^2.

The FIGRA values for the hypothetical products were calculated by predicting the HRR curves of the SBI test using the one-dimensional thermal flame spread model described above. The generated data files were used for finding an expression for FIGRA as a power law of t_{ig}, $\dot{q}''_{\max}$ and $t_{\max}$. On the basis of the exponents found by least squares fitting, the value of m = 0.89 was selected for the calculation of the I_Q index as shown in the Appendix of Paper II. Finally, another fit was performed in order to express FIGRA as a power law of I_{ig} and I_Q. The resulting regression equation is

$$\mathrm{FIGRA} = 2.7 \cdot 10^{-4}\ I_{ig}^{0.93}\ I_Q^{1.85} \qquad (16)$$

where I_Q is calculated with m = 0.89 according to Equation (14) and the unit of I_{ig} is min^{-1}.

It is noted that the selected ranges of $\dot{q}''_{\max}$, $t_{\max}$ and t_{ig} limit the validity range of the model. The prediction according to Equation (16) should not be used for products outside the validated range due to the increased uncertainty of the predicted FIGRA values.

The THR threshold values normally used in the FIGRA calculation according to prEN 13823 were ignored in the model development for analogy because the calculation of the rate of heat release index does not include any THR threshold. However, a corresponding regression equation can also be found for FIGRA values determined using the THR thresholds.

3.5 Fourier transform infrared spectrometry

The development of Fourier transform infrared (FTIR) spectrometry began with the invention of a two-beam interferometer by Michelson in the 1890's. Even though the principle of interferometry has been known for over a century, several breakthroughs in technology in the 1950's and 1960's were needed before FTIR spectrometry became an acceptable technique for measuring high-quality infrared spectra. At present, the FTIR method is used in a wide variety of spectrometric applications.

The Michelson interferometer is a device that divides a beam of radiation into two paths and then recombines the two beams after a path difference has been introduced. In this condition, interference between the beams can occur. The intensity variations of the beam emerging from the interferometer can be measured as a function of path difference by a detector. The principle of the Michelson interferometer is illustrated in Figure 3.

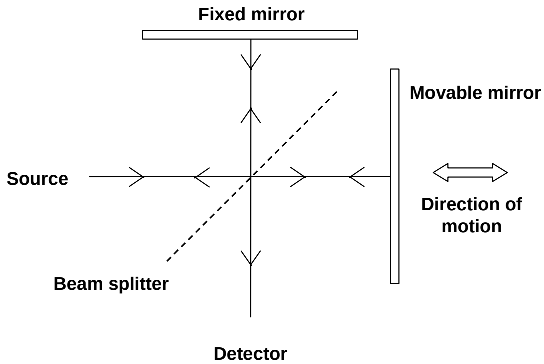

Figure 3. A schematic presentation of the Michelson interferometer.

The intensity of the beam at the detector is composed of constant and modulated components. The modulated component is generally referred to as the interferogram. The spectrum is obtained from the interferogram by computing the cosine Fourier transform, which accounts for the name of the spectrometric technique [118, pp. 1–6].

FTIR spectrometry is based on infrared (IR) absorption. Specific to the FTIR method is the conversion of an interferogram into a conventional wavelength spectrum containing information over a wide wavelength range. In a typical spectrum, absorbance is presented as a function of radiation in wave numbers.

In the FTIR analysis of smoke gases, gas samples are taken from a gas sampling system (e.g. an exhaust duct) or directly from the fire gases. The sample is drawn continuously through a heated sampling line to a heated IR absorption cell. An interfered IR beam is directed through the gas cell. A beam length inside the gas cell sufficient to accumulate adequate absorption for detection of gas components is obtained by reflecting the IR beam several times between mirrors at the ends of the cell before sending it to the detector. At chosen intervals, interferograms are recorded and converted into absorption spectra. The gas concentrations are calculated by analysing the absorption spectra. A schematic view of the FTIR measurement is shown in Figure 4.

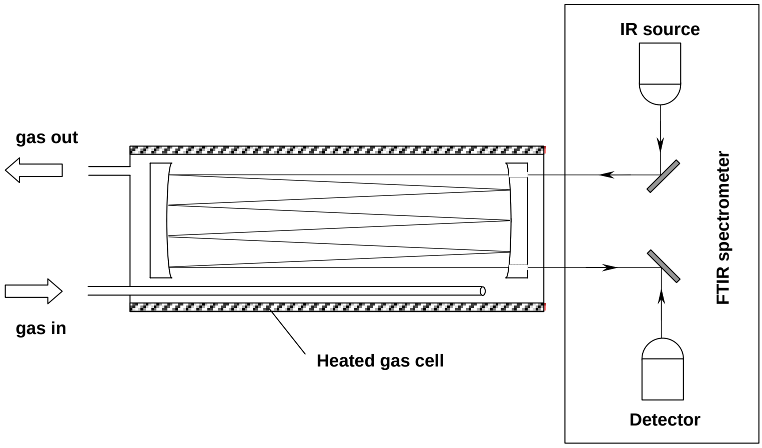

Figure 4. A schematic presentation of the FTIR measurement.

Polyatomic and heteronuclear diatomic compounds absorb energy at specific wavelengths due to the resonance of different types of molecular vibrations at specific frequencies. These compounds can thus be identified based on their characteristic absorbances. Concentrations are related to absorption intensities. The unknown concentrations of various species in a gas sample can be calculated on the basis of the areas of absorbance in the spectra recorded during the fire test and in the reference spectra with known gas concentrations. Several mathematical methods are available for quantitative determination of multicomponent smoke gases [119, 120].

A standard procedure for measuring smoke gas concentrations by the FTIR method has been adopted by Nordtest [51]. As a result of the SAFIR project described in Paper IV, the technique is undergoing standardisation in the ISO [121].

3.6 Experiments on wooden facades and compartments

The test arrangements of wooden facades and compartments were not based on any standard fire tests, but were designed specifically for the test series performed. Due to the size of the specimens, measurements of heat release rate were not carried out in the full-scale tests since the fire test facilities of VTT do not include an industry calorimeter. The main quantities measured were thus temperatures using thermocouples and heat fluxes using total heat flux meters.

3.6.1 Test arrangements for wooden facades

The experimental arrangement of the intermediate-scale facade tests is presented in Figures 1 and 2 of Paper V. The size of the test specimen consisting of a wooden frame, gypsum plasterboard, a ventilation cavity formed using wooden battens and the surface material to be studied was 1.2 m × 2.9 m. A 2.4 m high sample of the surface material was attached to the upper part of the specimen so that its lower edge was 0.5 m above the floor level. The ignition source was a sandbox burner of size 1.2 m × 0.1 m × 0.15 m, placed lengthways along the lower edge of the specimen. The heat output of the burner was 100 kW. The maximum exposure time was 30 minutes, but the test was interrupted earlier if the upper edge of the specimen was flaming extensively. Since the specimen was erected under a hood, the heat release rate could be measured. Other measurements included heat flux at the upper edge of the specimen and temperatures on the specimen surface and in the ventilation cavity. Flame spread on the front surface of the specimen was visually observed according to marker lines at intervals of 0.5 m.

The large-scale facade specimens were built on the front surface of a three-storey facade test rig made of lightweight concrete (see Figure 17 of Paper V). Two fire scenarios with different ignition sources, an external fire source and a post-flashover compartment fire, were studied using different test arrangements.

In the case of an external fire source, the size of the test specimens was 4.2 m × 5.6 m for two-storey facades and 4.2 m × 8.1 m for a three-storey facade as presented in Figure 15 of Paper V. The basic structure was similar to the intermediate-scale test specimens. The ignition source for the two-storey specimens was the same as used in the intermediate-scale tests, again at a heat output of 100 kW. For the three-storey specimen, two similar burners placed contiguously with a total heat output of 200 kW were used. The burning time of the burner(s) was 30 minutes. The tests were terminated when the upper edge of the specimen was extensively flaming or the flames on the specimen were nearly self-extinguished. During the tests, heat flux to the middle point of the window opening(s), surface temperatures of the specimen and temperatures in the ventilation cavity were measured. The ignition of the specimen and the flame spread on the front surface were visually observed.

In the tests using a post-flashover compartment fire as the ignition source, the specimens were installed above the window opening of a fire room in the ground storey of the facade test rig. The specimen area was usually 4.2 m × 5.6 m but variable as shown in Figure 18 of Paper V. The size of the fire room is 4.0 m × 2.6 m × 2.2 m (width × height × depth), and the size of its window opening is 3.0 m × 1.2 m (width × height). The opening factor of these tests was thus $O \approx 0.079\ m^{1/2}$. For one experiment, the width of the opening was narrowed to 1.2 m, resulting in $O \approx 0.032\ m^{1/2}$. The fire load consisted of wooden cribs stacked on the fire room floor, and particle boards attached to its back wall. The masses of the cribs and particle boards were normally 184 kg and 126 kg, respectively. With this fire load, the duration of the most intense heat exposure was approximately 15 minutes. During the tests, heat fluxes incident on the centre of the window openings on the first and second storey above the fire room were monitored. Temperatures were measured inside the fire room, on the front surface of the facade, in the ventilation cavity, and under and behind the eaves. The ignition of the specimen and the flame spread on the front surface were visually observed.

3.6.2 Test arrangements for timber construction compartments

Figure 1 of Paper VI shows schematically the experimental arrangement of the tests of timber construction compartments.

The test series included four different rooms. One of the rooms had a wooden stud frame with mineral wool insulation whereas the others were heavy laminated timber structures with a solid frame. The wooden construction was either unprotected or covered inside with one or two layers of gypsum plasterboard. The floor of the rooms was made of particle board with rockwool insulation. A facade mock-up made of non-combustible fibre cement boards and wooden frames was erected above the front wall.

The inner dimensions of the rooms were 3.5 m × 2.5 m × 4.5 m (width × height × length). The size of the window opening was 2.3 m × 1.2 m (width × height). These dimensions resulted in an opening factor of $O \approx 0.042\ \mathrm{m}^{1/2}$.

The movable fire load consisted of wooden cribs stacked in four piles inside the room as depicted in Figure 2 of Paper VI. An integral part of the fire load was the particle board flooring. The masses of the wooden cribs and particle boards were 680 kg and 230 kg, respectively. Assuming a net heat of combustion of 15.5 MJ/kg, the fire load density was approximately 900 $\mathrm{MJ/m^2}$ calculated over the floor area. If a combustion efficiency of 0.8 is assumed as suggested in prEN 1991-1-2 for mainly cellulosic materials [91], the fire load density was about 720 $\mathrm{MJ/m^2}$.

During the experiments, temperatures were measured inside the room, between and/or behind gypsum plasterboard on the ceiling and walls, and under the particle board flooring. Charring of wood behind the gypsum plasterboard was monitored using thermocouples embedded in wooden blocks inserted into the ceiling and a sidewall. Heat flux from the flames incident on the facade mock-up was measured using a total heat flux meter 2.2 m above the upper edge of the window opening.

3.7 Measurement uncertainty

When examining experimental data, the uncertainties related to measurement results must be taken into consideration. Even though test results are commonly reported as single values or curves, they always include uncertainties depending on instrument accuracy, test procedures, approximations in calculations etc.

The uncertainty of measurement results can be evaluated by statistical analysis of a series of observations (type A evaluation) or by other means (type B evaluation). Type B evaluation is usually based on scientific judgment using all the relevant information available, including previous measurement data, experience with, or general knowledge of, the behaviour and properties of relevant materials and instruments, manufacturer's specifications, data provided in calibration and other reports, and uncertainties assigned to reference data taken from handbooks [122].

Each component that contributes to the uncertainty of a measurement is represented by an estimated standard deviation, termed standard uncertainty. The combined standard uncertainty of a measurement is obtained by combining the individual standard uncertainties arising from a type A or a type B evaluation. The method of combination is called the law of propagation of uncertainty or the "root-sum-of-squares" method. The expanded uncertainty is obtained by multiplying the combined standard uncertainty by a coverage factor k chosen at the desired level of confidence. A common practice is to use the value k = 2 related to a level of confidence of approximately 95 %, assuming normal distribution of measurement results [123].

In the case of the type A evaluation, standard uncertainties are represented by estimated standard deviations. The precision of a test method is usually presented as repeatability and reproducibility standard deviations s_r and s_R, respectively, or as relative values s_r/m and s_R/m obtained by dividing by the general mean m. Precision can also be expressed as repeatability and reproducibility limits r and R, respectively. These are the values less than or equal to which the absolute difference between two test results obtained under repeatability/ reproducibility conditions may be expected to be with a probability of 95 % [124]. The repeatability and reproducibility limits can be approximated as $r \approx 2.8\, s_r$ and $R \approx 2.8\, s_R$. Repeatability refers to independent test results measured with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time. Reproducibility is related to test results obtained with the same method on identical test items in different laboratories by different operators using different equipment.

3.7.1 Heat release rate

Related to heat release rate measurement of room fires, Yeager has calculated the measurement uncertainty as a combination of uncertainties of gas analysis, volume flow rate and heat production constant of oxygen consumption [125].

According to his findings, the relative uncertainty increases with decreasing volume flow rate and heat release rate. At heat release rates and volume flow rates typical for room fire experiments, the relative uncertainties varied from ±5 % to ±11 %. It is noted, however, that Yeager did not use a coverage factor in the calculations.

Enright and Fleischmann have studied the uncertainty related to the heat release rate calculation of the cone calorimeter according to the ISO 5660-1 standard [126]. They demonstrated that the most significant uncertainty sources are the assumed effective heat of combustion term, the combustion expansion assumption and the instrument uncertainty of the oxygen concentration measurement. The study deals with combined uncertainties without a coverage factor. Analysing their example, relative uncertainties from ±5 % to ±10 % can be obtained at heat release rates larger than approximately 50 kW/m^2. At lower HRR levels, the contributions of the combustion expansion assumption and the oxygen analyser increase the uncertainty of the calculation. A relative uncertainty of less than ±5 % is not possible at any HRR level due to the uncertainty of the assumed effective heat of combustion.

Axelsson et al. [127] have given guidelines for estimating the magnitude of individual error sources and calculating the combined expanded uncertainty for HRR and smoke production rate measurements. In their case study, combined expanded uncertainties from ±7 % to ±14 % (k = 2) in the HRR measurements of Room/Corner and SBI tests were found. In the case of the SBI test, however, the uncertainty of HRR results is reduced to ±(3–5) % due to the 30-s averaging in the data processing according to the prEN 13823.

The repeatability and reproducibility of the cone calorimeter and the SBI test have been determined in interlaboratory trials. For the cone calorimeter, the relative repeatability and reproducibility standard deviations s_r/m and s_R/m are in the ranges of 3–55 % and 4–87 %, respectively, for the maximum and total heat releases [12, 128]. An interlaboratory trial for the SBI test was arranged in connection with the method development. Averages of s_r/m and s_R/m for the numerical classification parameters are given in Table 1 [5]. Data with very small mean values have been excluded from the averages since they deviate from the general level. Small parameter values typically have large relative standard deviations due to small mean values even though the absolute values of the standard deviations are low.

Table 1. Average relative standard deviations for the classification parameters of the SBI test [5]. The subscripts of FIGRA refer to the THR thresholds used in the calculation according to prEN 13823.

	$FIGRA_{0.2MJ}$	$FIGRA_{0.4MJ}$	THR_{600s}	SMOGRA	TSP_{600s}
Average s_r/m	14 %	15 %	11 %	15 %	18 %
Average s_R/m	23 %	25 %	21 %	40 %	44 %

3.7.2 FTIR measurement and analysis

The uncertainty of FTIR results cannot be evaluated using the type B approach due to the mathematical complexity of various analysis techniques. For determining the repeatability and reproducibility of the FTIR method, an interlaboratory trial was performed as a part of the SAFIR project. Calculated over all materials and gas species included in the statistical analysis, the averages of s_r/m and s_R/m were 12 % and 25 % for maximum concentration values and 10 % and 30 % for yields, respectively. The procedure and results of the interlaboratory trial are presented in more detail in Paper IV.

3.7.3 Temperature measurements

Measurements of gas and surface temperatures naturally have an important role in fire research. In most cases, temperatures are measured by thermocouples because of the ease of installation and use. The most suitable thermocouple type for fire experiments is type K, due to its wide temperature range (from -200 °C to +1260 °C) and good oxidation resistance [129, pp. 43–51]. The measurement accuracy of type K thermocouples used in the experiments presented in this thesis is ±1.5 °C up to 400 °C. At higher temperatures, the accuracy deteriorates linearly being ±4 °C at 1000 °C.

The main problem in determining surface temperature is to make the measurement without significantly disturbing the measured object. The most significant errors in the surface temperature measurement can be introduced through changes in local heat transfer conditions, uncertainty of the position of the thermocouple junction, and heat losses by conduction along the thermocouple wires when they are placed in strong temperature gradients [130, pp. 5–8]. To minimise these errors, the thermocouples should have as small a diameter as possible, and the junction should be in good thermal contact with the surface. Furthermore, the error due to conduction along the thermocouple wires can be reduced by placing a sufficient length of wire near the hot junction, perpendicular to the temperature gradient [130, pp. 5–8].

When gas temperatures are measured using bare thermocouples inside or near to flames, the heat transfer by radiation between the thermocouple, flame and surroundings causes measurement errors. Temperatures measured are underestimates inside flames, and overestimates outside flames, compared to real temperatures.

3.7.4 Model sensitivity

The sensitivity of the FIGRA predictions of the one-dimensional thermal flame spread model on the input data is discussed in Paper I. Relative changes of ±10 % and ±20 % were artificially introduced to ignition times t_{ig} and maximum heat release rates $\dot{q}''_{\max}$ of selected cone calorimeter curves used as the model input. The selection of materials for the sensitivity study included products with varying fire performance and classes. The changes induced to FIGRA values are presented in Tables 4 and 5 of Paper I. On average, the relative change of FIGRA was larger than the relative change of t_{ig} or $\dot{q}''_{\max}$. No clear dependence on the magnitude of FIGRA was observed, even though the relatively small FIGRA values of classes A2/B and C seemed to be more sensitive to the variation of input data than higher values corresponding to class D.

The sensitivity of the FIGRA predictions obtained using the model based on rate of heat release and ignitability indices is considered in Paper II. The effects of variation in I_{ig} and I_Q on FIGRA values can be seen directly by differentiating Equation (16). From the exponents, it can be observed that FIGRA is approximately twice as sensitive to I_Q as to I_{ig}. A change of I_{ig} results in a comparable change of FIGRA, because FIGRA $\propto I_{ig}^{0.93}$. In contrast, a change of I_Q causes a much larger change of FIGRA, since FIGRA $\propto I_Q^{1.85}$. The effect of variation of $\dot{q}''_{max}$ or $\dot{q}''(t)$ on predicted FIGRA values is not as straightforward since I_Q is not directly proportional to the heat release rate. Examining the artificial cone calorimeter data used in the model development it was found that a change of 10 % of $\dot{q}''_{max}$ results in a change of approximately 15 % of FIGRA. Thus, FIGRA is overly sensitive to $\dot{q}''_{max}$.

The changes of predicted FIGRA values due to the variation of cone calorimeter data naturally have an effect on predicted classifications. However, classifications based on SBI tests also vary, especially for products close to a limit between two classes. This kind of borderline product cannot be completely avoided, no matter how carefully a classification system is designed.

4. Results and discussion

The main results of Papers I–VI are summarised in this chapter. The models developed for predicting SBI test results are compared. The relations of the European and Japanese fire classification systems of surface linings are presented. The results of a European research project of smoke gas analysis by FTIR spectrometry are reviewed. Two fire scenarios related to wooden facades are introduced with principles of formulating acceptance criteria. Finally, fire development in timber construction compartments is described.

4.1 Correlation of cone calorimeter and SBI test results

In Papers I and II, two models for predicting the results of the SBI test on the basis of cone calorimeter data are introduced. The one-dimensional thermal flame spread model (see Section 3.4.1) can be used to predict the first peak of the heat release rate curve of a product in the SBI test. Estimates of the FIGRA value and the classification can be determined on the basis of the predicted curve. The model based on rate of heat release and ignitability indices (see Section 3.4.2) predicts the FIGRA value and the classification using a simple regression equation. However, the heat release behaviour of a product cannot be estimated using this approach.

4.1.1 Prediction of the heat release rate

A series of graphs comparing the measured HRR curves against those predicted was obtained using the one-dimensional thermal flame spread model. This model is incapable of reproducing the shape of the HRR curve throughout the whole SBI test, but the first HRR peak can be predicted relatively well. Prediction of the first peak is usually adequate for predicting the classification of a product correctly, since the early part of the test is of major importance determining the FIGRA value.

Investigation of the modelled heat release rate curves revealed three product groups: basic wood products, wood products with a surface layer, and products with a surface layer on a non-combustible substrate. Examples of the measured and predicted HRR curves are shown in Figures 5–8 of Paper I.

For basic wood products, the model predicts the first peak of the HRR curve reasonably well. The predicted heat release rates for wood products with a surface layer tend to be delayed and smoothed compared to the SBI measurements. Products composed of a surface layer on a non-combustible substrate show two types of behaviour depending on the thickness of the surface layer. If the surface layer is thin, the calculated HRR curve exhibits a sharp peak in the beginning of the test. In the SBI test, this peak (if observable) is lower and smoother, and it usually occurs earlier than predicted. If the surface layer is thicker, the predicted peak is both wider and more consistent with the SBI measurement.

Outside these groups there are some products for which the modelling is unsuccessful, owing either to the limitations of the model or to the different features of the SBI and cone calorimeter test methods. For materials exhibiting extensive flame spread, the compensation procedures of the one-dimensionality of the model are inadequate. The model involves assumptions for the scaling of the ignition time and the width of the pyrolysis area that are not optimal for fire-retarded materials. For materials that melt, and for products with a reflective coating, the predictions are unsuccessful because the SBI apparatus and the cone calorimeter have different heat transfer modes and different test arrangements with regard to the specimen orientation and the ignition source.

4.1.2 Comparison of the models

The one-dimensional thermal flame spread model and the I_Q-I_{ig} index model have been applied to a set of 35 construction products [131], including materials from the interlaboratory trial of the SBI test development [117] and from the Japanese Fire Test SOPRO programme [132]. In Papers I and II, slightly smaller material sets were included. The products studied can be regarded as a representative selection of typical construction products with varying reaction-to-fire performance.

The comparison of FIGRA and classification predictions of the one-dimensional thermal flame spread model and the I_Q-I_{ig} index model is presented in Figure 5. The highest FIGRA values are excluded for clarity. For the I_Q-I_{ig} index approach, only the results within the validated range of the model are shown.

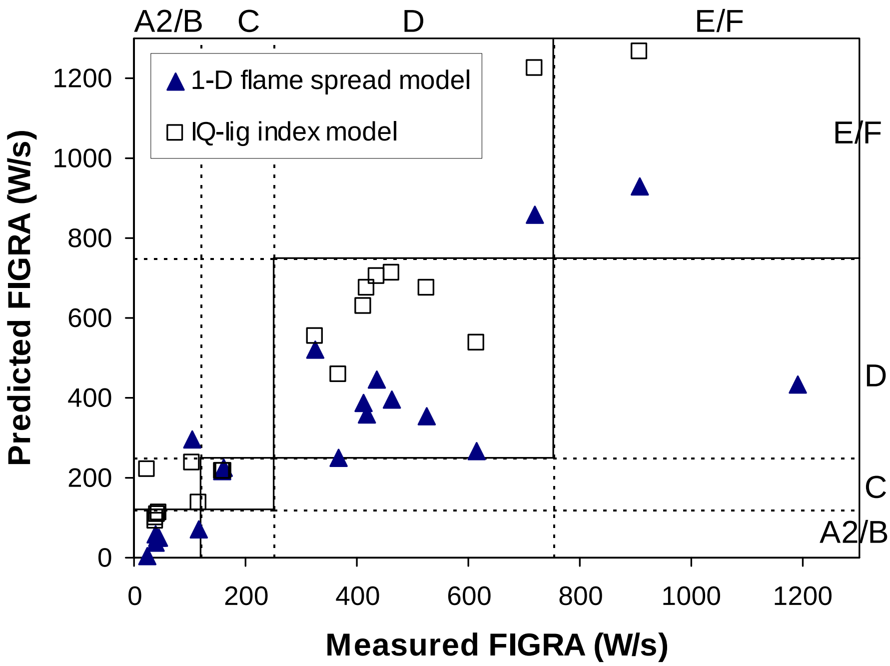

Figure 5. Comparison of measured and predicted FIGRA values for the one-dimensional thermal flame spread model and the I_Q-I_{ig} index model. The letters in the margins refer to the Euroclasses, and the class limits are shown by dotted lines. The areas limited by solid lines show the consistency of classifications by modelling and experiments.

Figure 5 indicates that the FIGRA values predicted by the I_Q-I_{ig} index model tend to be systematically on the safe side, i.e. the predicted values are higher than the experimental results. For the one-dimensional thermal flame spread model, the predicted FIGRA values fall on both sides of the diagonal of Figure 5, showing no bias to either safe or unsafe predictions.

To clarify the prediction of classification, the predicted and measured Euroclasses for the products studied are presented in Table 2 for the one-dimensional thermal flame spread model and in Table 3 for the I_Q-I_{ig} index model. The code numbers of the products can be found in Table 2 of Paper I and Table 1 of Paper II.

Table 2. Comparison of measured and predicted classification for the one-dimensional thermal flame spread model. The underlined products showed no sustained flaming or had an ignition time too long for calculations (i.e. class A2/B predicted).

Predicted class

		A2/B	**C**	**D**	**E/F**
SBI class	**A2/B**	M01 <u>M06</u> M08 M11 M13 <u>M14</u> <u>M15</u> <u>M19</u> <u>M21</u> M27 M28 <u>7-K</u> 7-R <u>9-K</u>		M02	
	C		M09 M29 10-B		
	D			M10 M12 M16 M20 M22 M23 M24 M25 7-G 7-Q1 10-A	M05
	E/F	M04		M07	M03 M26 M30

Certain products are outside the scope of the modelling calculations due to their ignition properties. In both models, the ignition in the cone calorimeter test is assumed to take place when the heat release rate per unit area reaches 50 kW/m^2. If the heat release rate of a product never reaches 50 kW/m^2, the calculations cannot be performed. Furthermore, the one-dimensional thermal flame spread model scales the ignition time to a lower exposure level. If the scaled ignition time exceeds the duration of the SBI test, the calculation is not feasible. In practice, however, such products meet the requirements of class A2/B in the SBI test. Thus, these types of ignition behaviour can be included in the class prediction of the models as special cases.

In the case of the one-dimensional thermal flame spread model, the predicted classification differs from the experimental result only for four products. Two of these products (M02 and M04) belong to product groups recognized problematic, one of them (M05) is a borderline product near the limit of classes D and E, and the fourth one (M07) exhibited considerable scattering of experimental classifications in the interlaboratory trial of the SBI test development.

Table 3. Comparison of measured and predicted classification for the I_Q-I_{ig} index model. The underlined products showed no sustained flaming (i.e. class A2/B predicted). The products in parentheses are out of the validated range of the model (i.e. t_{ig} < 5 s or t_{ig} > 60 s).

Predicted class

SBI class		**A2/B**	**C**	**D**	**E/F**
	A2/B	M01 (M06) M08 M13 (M14) M15 M19 M21 M27 7-K 7-R 9-K	M02 M11 M28		
	C		M09 M29	10-B	
	D			M10 M12 M16 M20 M22 M23 M24 M25 7-G 7-Q1 10-A	M05
	E/F	(M04)		(M07)	M03 M26 (M30)

The products obtaining an incorrect class prediction using the one-dimensional thermal flame spread model are classified incorrectly also using the I_Q-I_{ig} index model. In addition, the class prediction of the index approach fails for products exhibiting a small HRR peak (5–12 kW) in the early stage of the SBI test, followed by a negligible heat release. For this kind of product, the THR thresholds of the FIGRA calculation have a significant effect on FIGRA values. The reason for these incorrect class predictions is the model development ignoring the THR thresholds. However, the predictions are on the safe side compared to the experimental results.

In conclusion, the one-dimensional thermal flame spread model presented in Paper I works reasonably well for products with minor or moderate lateral flame spread in the SBI test. For these materials, the one-dimensionality of the model can be compensated by the selection of input parameters. In the data set studied, the classification on the basis of FIGRA was predicted correctly for 24 out of 28 products (i.e. 86 %). Including the products exhibiting no sustained flaming or ignition times too long for the modelling calculations, 89 % of the class predictions were successful.

The predictive procedure based on the rate of heat release and ignitability indices presented in paper II gave correct classification for 20 out of 25 products studied (i.e. 80 %) within the validated t_{ig} range of the model. If the products without sustained flaming in the cone calorimeter tests are included, the success rate of the class prediction increases to 83 %.

In the SBI Round Robin results for all 30 products and 15 laboratories, 93 % of classifications were in the class to which the majority of results for each product belonged. The success rates of both models can therefore be considered satisfactory.

There are two important differences between the cone calorimeter and the SBI test that affect all modelling attempts. Firstly, the heat exposure in the cone calorimeter test is radiative and well defined whereas the SBI test includes flame impingement producing a non-constant exposure on the specimen surface, leading to different behaviour of, for example, materials covered by a reflective coating. Secondly, physical effects in the SBI test (edges, joints, bending, collapsing, etc.) are not observed in the cone calorimeter test. Therefore, a model based on cone calorimeter test results cannot simulate all features of the SBI test.

Either of the models presented above can be used for predicting FIGRA values and Euroclasses. However, when using the mathematically simpler I_Q-I_{ig} index approach, the limited validity range of the model must be noted. If the shape of the heat release rate curve needs to be modelled, the one-dimensional thermal flame spread model must be applied.

The essential feature of both models is that only a single cone calorimeter test at a single heat exposure level is required as input, without a need of any additional data or material parameters. Thus, the models provide practical and economical tools for product development and quality control.

4.2 Comparison of fire classification of surface linings in Japan and Europe

The Building Standard Law (BSL) of Japan has recently undergone a revision. Before the reform of BSL, the Japanese fire classification system was based on national fire test methods including the Japanese non-combustibility test, the surface test, the heating test on a perforated specimen, the toxicity test, and the Japanese model box test described in Notifications No. 1828 [133] and No. 1231 [134]. The new fire regulations are based on international standard fire tests including the non-combustibility test ISO 1182 [135], the cone calorimeter test ISO 5660-1 [12], and the reduced-scale model box test ISO/CD 17431 [136]. Additionally, the Japanese toxicity test is required for products with a decorative finish exceeding a fixed quantity of organic compounds.

Similarly to the previous fire regulations of surface linings, the new Japanese classification system includes three classes of fire preventive materials: non-combustible, quasi-non-combustible and fire retardant materials. In order to be classified as a fire preventive material in Japan, the heat release rate and the total heat release of a construction product must not exceed 200 kW/m^2 and 8 MJ/m^2, respectively, in a cone calorimeter test at the heat exposure level of 50 kW/m^2 in horizontal orientation. The time period of evaluation depends on the class pursued, being 5 minutes for non-combustible materials, 10 minutes for quasi-non-combustible materials and 20 minutes for fire retardant materials. A detailed summary of the Japanese class requirements for various fire test methods is given in Table 5 of Paper III.

Paper III deals with the comparison of the forthcoming Euroclasses and the new Japanese fire classification system concentrating on the heat release of construction products. Smoke production, flaming droplets/particles and toxicity are out of the scope of the study since these aspects are not included in both classification systems.

The Japanese and European fire classification systems have a common reference scenario, a fire in a small room represented by the ISO 9705 Room/Corner test [17]. The basic principle of both systems is to relate the class limits to the time to flashover in the Room/Corner test. In the development of the Euroclass system, the class limits were defined on the basis of a fire growth rate index $FIGRA_{RC}$, calculated as the quotient of the maximum heat release rate of the specimen and its occurrence time [137]. The flashover in the Room/Corner test is usually interpreted as taking place when the sum of the heat release rates of the burner and the specimen reaches 1 MW. Knowing the heat output sequence of the burner, $FIGRA_{RC}$ can be related to the time to flashover as explained in Paper III.

The reference scenario class limits of the Euroclasses and the Japanese classification are shown in Figure 6. According to the reference scenario performance, products classified as non-combustible materials in Japan belong to Euroclasses A1, A2 and B. Euroclass C corresponds to the Japanese class of quasi-non-combustible materials. Euroclass D products are regarded as either fire retardant or unclassified materials in Japan, depending on their time to flashover in the Room/Corner test.

<table>
<tr><th>FIGRA_{RC} (kW/s)</th><th>0.16</th><th>0.58</th><th>1.5</th><th>3.0</th><th>7.5</th><th></th></tr>
<tr><td>Euroclass</td><td>A1/A2</td><td>B</td><td>C</td><td colspan="2">D</td><td>E/F</td></tr>
<tr><td>Japanese class</td><td colspan="2">nc</td><td>q-nc</td><td>fr</td><td colspan="2">uc</td></tr>
<tr><td>Time to FO</td><td>no FO</td><td>20 min</td><td>10 min</td><td>5 min</td><td>2 min</td><td></td></tr>
</table>

Figure 6. Reference scenario class limits of Euroclasses and Japanese classification in terms of $FIGRA_{RC}$ index and time to flashover in the Room/Corner test (FO = flashover, nc = non-combustible, q-nc = quasi-non-combustible, fr = fire retardant, uc = unclassified).

The class correspondence presented in Figure 6 is based on the assumed reference scenario behaviour of the products. The actual classification, however, is determined on the basis of the classification test methods without performing the Room/Corner test. The Japanese system is based mainly on the cone calorimeter, whereas the most important European test method for products exhibiting a non-negligible contribution to fire is the SBI test. Thus, the European fire classification of a construction product can be predicted from the results of the Japanese classification test using the models introduced in Sections 3.4.1 and 3.4.2.

A comparison of Japanese and European classifications for 35 construction products is presented in Table 4. The classes of the products were determined on the basis of cone calorimeter and SBI tests. The cone calorimeter tests were run originally for purposes other than determining classification. Therefore, the duration of some tests was not sufficient for evaluating the Japanese class. For these products, estimated classification was obtained by extrapolating the heat release data to 10 or 20 minutes for calculating the total heat release. The class estimates are shown in parentheses in Table 4.

The Japanese and European fire classifications are in agreement considering the reference scenario for two thirds of the products studied. However, certain product groups showing inconsistency can be found.

Products consisting of a thin surface layer on a non-combustible medium or high-density substrate usually get a lower Japanese class (quasi-non-combustible or fire retardant) than expected on the basis of their Euroclass (A2/B). After an initial HRR peak due to the surface layer, these products produce heat at a relatively low level. However, a heat release level of 10–15 kW/m^2 is high enough to exceed the total heat release limit of 8 MJ/m^2 in 10 or 20 minutes.

The consistency of the classification systems for materials showing no sustained flaming in cone calorimeter tests is good. These products are classified as non-combustible materials in Japan and as A2/B class products in Europe. However, if a product ignites after a relatively long heat exposure and produces a notable amount of heat after the ignition in the cone calorimeter test, its heat release can lead to classification as a fire retardant or even an unclassified material in the

Japanese system. The European class on the basis of FIGRA can still be A2/B for this kind of product.

More problematic are products consisting of a thin, combustible surface layer on a non-combustible low-density substrate (for example, paper-faced glass wool). This combination leads to rapid flame spread and a very short time to flashover in the Room/Corner test. In the cone calorimeter test, the surface layer burns quickly away producing a short-termed HRR peak. After that, the heat release is practically zero. Thus, the product is classified as a non-combustible material in Japan.

Table 4. Comparison of the Japanese and European fire classifications based on the cone calorimeter and SBI tests. The shaded cells show the expected positions of the products based on the reference scenario judgment.

Europe

Japan	**A2/B**	**C**	**D**	**E/F**
nc	M11 (M15) M19 (M21) (M28) (7-K) 7-R 9-K	10-B		M30
q-nc	(M01) (M13)			
fr	M06 M08 M27	(M09) (M29)	10-A	
uc	M02 M14		M05 M10 M12 M16 M20 M22 M23 M24 M25 7-G 7-Q1	M03 M04 M07 M26

nc = non-combustible material
q-nc = quasi-non-combustible material
fr = fire retardant material
uc = unclassified material
( ) = class estimate

In general, if the Japanese and European classifications are inconsistent, the Japanese classification system usually leads to an increased safety level compared to the Euroclasses. However, exceptional cases like the previous example should be noticed and methods for eliminating this kind of fire safety risk should be examined.

The Japanese fire classification system is relatively simple and easy to learn. The evaluation time of the classification quantities is specific to each class, but the numerical values of the class limits in the cone calorimeter test remain the same in all classes. However, a noteworthy detail is the lack of requirements for the time to ignition. In general, ignitability is regarded as an important parameter since the correlation between time to ignition and flame spread has been proven [15]. Ignition time criteria would prevent the overrating of easily ignitable products regardless their heat release performance after ignition.

The Japanese classification system includes alternative test methods for the cone calorimeter: the non-combustibility test ISO 1182 for non-combustible materials and the reduced-scale model box test ISO/CD 17431 for quasi-non-combustible and fire retardant materials. The criteria of the (prEN) ISO 1182 test for non-combustible materials in Japan are more demanding than those for class A1 products in Europe. On the other hand, a product classified as a non-combustible material using the cone calorimeter does not necessarily meet the requirements of class A2 in the prEN ISO 1716 test. This observation brings forward the question of the comparability of the Japanese class criteria defined for the non-combustibility test and the cone calorimeter.

It is noted that also the European classification system has some problematic issues. Certain types of products have been found difficult to test using the Euroclass test methods [138]. It should also be borne in mind that the Euroclass system is based on the cooperation and decisions of several parties in different countries. Thus, it includes many compromises.

In conclusion, the Euroclass of a product cannot be directly determined from its Japanese class (or vice versa), despite the common reference scenario. For the majority of the products, however, the classification systems are strongly consistent. The inconsistencies due to the different test methods and classification quantities can be detected by recognizing the materials of the product groups known to be problematic.

4.3 FTIR spectrometry in smoke gas analysis

As described in Paper III, the combustion toxicity of surface linings is determined in Japan using the Japanese toxicity test. The test is used for the customary reasons, even though it is ethically controversial due to the use of animals as indicators of the toxicity of combustion gases. However, alternative methods for the evaluation of smoke gas toxicity are available.

The use of FTIR spectrometers overcomes many of the conventional problems of smoke gas analyses as described in Section 2.4. However, difficulties relating to large amounts of soot and water vapour in the fire test environment have been recognised. Furthermore, adsorption of gases onto soot particles and interferences between overlapping spectra from individual gas components are known to cause measurement inaccuracies.

Paper IV describes the results of the SAFIR (Smoke Gas Analysis by Fourier Transform Infrared Spectroscopy) project that aimed at solving these problems. The main objective of the project was to further develop the FTIR analysis of smoke gases into an applicable and reliable method for determining toxic gas components in fire test conditions. The SAFIR project was divided into five work packages[1]: WP1 – Sampling in small scale; WP2 – Sampling in large scale; WP3 – Data analysis, calibration and software; WP4 – Verification in different fire scenarios; and WP5 – Interlaboratory trial. The contents and results of the work packages are described in detail in the final report of the project [139]. As a result of the SAFIR project, a draft standard of the FTIR method for smoke gas analysis [121] was prepared and forwarded to standards organisations.

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[1] The author contributed to work packages WP1, WP4 and WP5. For completeness, however, the results of work packages WP2 and WP3 also are briefly discussed in the following sections.

4.3.1 Sampling

The main problem of the FTIR measurements in connection with fire test environments has been the acquisition of a representative sample of fire gases for analysis. In the SAFIR project, the design principle for an optimal sampling system was to aim at a rapid transfer of fire effluents unaltered through the sampling device. As a result of studies of the probe, filter, sampling line and gas cell, the sampling system shown in Figure 7 was recommended.

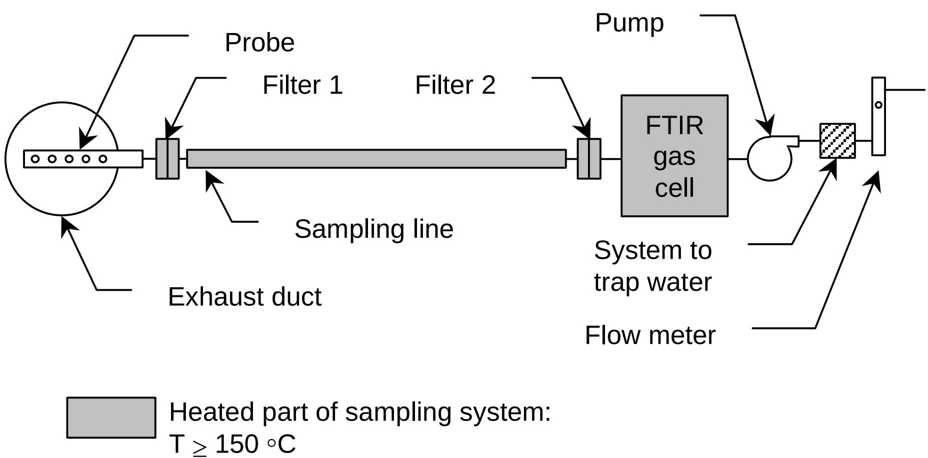

Figure 7. A schematic diagram for the optimised FTIR sampling system (not to scale).

The following recommendations were given to ensure the representativity of the smoke gas samples for analysis:

- A multi-hole probe made of stainless steel with a minimum hole diameter of 3 mm and holes oriented downstream is recommended. The position of the probe should be as close as possible to the combustion to avoid condensation, while still ensuring a homogeneous gas mixture and undisturbed gas flow for sampling.
- Both circular and cylindrical filters can be used. The main filter must be placed between the probe and the sampling line. To protect the gas cell from fine soot particles, another filter can be used between the line and the gas cell.

- A gas sampling line made of PTFE with an inner diameter of 3–4 mm exhibits an acceptable performance. The flow rate in the sampling line must be as high as possible, at least 3.5 l/min. The sampling line should be as short as possible, preferably no more than 4 metres.
- The flow meter must be positioned after the pump. Trapping of water between the pump and the flow meter is advisable.
- The pressure in the gas cell must be monitored during the experiments because pressure variations can lead to significant changes of measured concentrations.
- The temperature of the sampling system must be at least 150 °C and as even as possible in all parts of the device. The practical maximum is 190 °C to avoid softening of PTFE. If the same temperature cannot be maintained in all parts of the system, the temperature should preferably increase towards the end of the device.
- When acid gases are analysed, especially in low concentrations, the parts of the sampling device should be washed after the experiment and the washing solution should be analysed to evaluate the total amount of acid gases produced by combustion. For reliable results, the initial Cl and Br amounts in filters should be determined before use.

The recommendations above are applicable to both small and large-scale fire experiments. On the large scale, certain specific features must additionally be considered. When measuring gases that are not well mixed (e.g. in the door of a fire room), a multi-hole probe with a graded hole size (i.e. increasing in size away from the pump) should be used for the representativity of the gas sample. If the sampling line cannot be kept short due to the size of testing facilities, it is advisable to wash the line after the test to check for adsorbed acids.

In addition to the FTIR method, the recommendations for the sampling technique are applicable to all other methods used for determining gas concentrations in connection with fire experiments.

4.3.2 Calibration, analysis and software

In WP3 of the SAFIR project, the emphasis was put on the determination of the minimum detection limits of various species, the quality of reference spectra used in the spectral analyses, and the reliable model building for gas analysis.

Minimum detection limits depend on the pathlength and the signal-to-noise ratio. The noise level is determined by the source intensity, the number of scans, the spectral resolution, the type of optical filters, the stability of optical components, and the quality of the detector. A spectral line of a particular gas can be detected when it is approximately as high as the noise level present in a real smoke gas spectrum. A procedure for estimating the minimum detection limits of various gas components is given in Paper IV. The increased relative uncertainty of measured gas concentrations close to the minimum detection limit must be noted when reporting FTIR measurement results.

The reference spectra used in the spectral analyses must be recorded using the same experimental settings (path length, resolution, sampling device temperature etc.) with which the real smoke gas spectra will be recorded. A suitable number for reference spectra with different concentrations is 3–4 for gases showing a linear relationship between the area of absorbance and the concentration, whereas 5–6 concentrations are needed for non-linear species. The concentration range of interest for the prediction must be covered by the selection of reference gas concentrations. In the spectral analysis, extrapolation of concentrations outside the calibration range should be avoided.

Multivariate chemometrical techniques are needed for the prediction of toxic components in smoke gases generated during fire tests. For most gas species, non-linear techniques such as INLR and QTFA are needed. Visual inspection of the output of multivariate models is strongly recommendable. Reasons for unexpected behaviour must be investigated.

Reliable analysis of FTIR spectra from fire experiments requires that the analyst understands the basic principles of the analysis method in use. The assessment of the plausibility of the output of the prediction models is of crucial importance.

4.3.3 Verification of results, repeatability and reproducibility

To verify the usability of the FTIR method in the fire test environment, the FTIR response was compared quantitatively to the response of alternative measurement methods known to be capable of giving reliable results in smoke gas analysis.

The fire test methods included in the verification study were the cone calorimeter [12], the Purser furnace [140], the cumulative smoke chamber test [141], the SBI test [5] and the Room/Corner test [17]. The fire types represented by these methods were non-oxidative pyrolysis, well ventilated flaming, a small, vitiated fire in a closed compartment, and a post-flashover fire in an open compartment.

The materials for the verification tests were chosen to provide key gas species as combustion products, some of which were known to be problematic in fire gas analysis. The fuels and the combustion products of interest are summarised in Table 1 of Paper IV. The alternative analysis methods were non-dispersive infrared spectrometry (for CO and CO_2), high-performance ion chromatography (for HCl, HBr, HCN and SO_2), photometry (for HCN), chemiluminescence (for NO_x) and high-pressure liquid chromatography (for acrolein).

Considering the fire test characteristics, the concentration-time profiles measured by the FTIR method were realistic and followed the shape of the profiles from the comparison methods. The FTIR spectrometry gave good peak response.

The differences between the FTIR and comparison method results were calculated for total yields and, if possible, for maximum concentrations. The evaluation quantity, “FTIR deviation”, was defined as follows:

$$\text{FTIR deviation}\,(\%) = \frac{\text{FTIR result - Comparison method result}}{\text{Comparison method result}} \times 100\% \qquad (17)$$

The findings of the verification study are summarised in Table 5, including the species for which FTIR deviation estimates were obtained from at least two laboratories. Numerical FTIR deviation data for CO and CO_2 are given in Table 4 of Paper IV.

Table 5. FTIR deviation characteristics of the verification study.

Species	**No. of labs**	**FTIR deviation characteristics**
CO_2	7	Generally good agreement, laboratory dependent FTIR deviation (positive or negative)
CO	7	Generally good agreement, laboratory dependent FTIR deviation (positive or negative)
HCl	4	3 labs: high positive deviation *) 1 lab: good agreement
HCN	4	2 labs with sufficient concentrations: ca. +50 % Zero or trace level: no false positive FTIR results
NO	2	Reasonable agreement within ±20 %

*) Possibly difficulties with the comparison method

When the concentration levels measured were close to the minimum detection limit, the relative FTIR deviations were often exceptionally high. In some cases, the reason for the problems was the comparison method rather than the FTIR measurement.

The sign of the FTIR deviation was typically laboratory dependent, suggesting that the difference between the results of the methods compared is due to the measurement procedure of each laboratory, related to either the FTIR measurement or the alternative method. Systematically positive or negative deviations in all laboratories were not detected for any species or fire test methods.

To summarize, the verification study showed that the FTIR method is capable of making time-resolved measurements from fire gases for several species simultaneously. The recommendations of the small and large scale sampling studies were thus verified.

To determine the precision of the FTIR analysis of smoke gases in real fire tests, an interlaboratory trial was performed. FTIR measurements were performed in nine laboratories in connection with the cone calorimeter. The tests were run at the heat exposure level of 50 kW/m^2 and using horizontal specimen orientation. Three materials in three replicates were included. The repeatability and reproducibility were calculated according to the ISO 5725 principles [124] for both cone calorimeter and FTIR spectrometry quantities.

The relative repeatability and reproducibility standard deviations (s_r/m and s_R/m, respectively) for cone calorimeter quantities are presented in Table 5 of Paper IV. The precision of the cone calorimeter results was normal for a fire test method. Thus, the effect of the variability of the cone calorimeter test procedures on the scattering of the FTIR results can be considered typical for well-defined fire tests.

The s_r/m and s_R/m values of the FTIR results are summarized in Table 6 of Paper IV. The average s_r/m and s_R/m values were 12 % and 25 % for maximum concentrations and 10 % and 30 % for yields, respectively, calculated over all materials and species included in the statistical analyses.

The evaluation of the quality of the repeatability and reproducibility parameters is not straightforward. The answer to the question “What range of s_r/m and s_R/m values can be considered good/acceptable/poor?” is dependent at least on the nature of the measured quantity and the special features of the test method. To give some indication for the interpretation of the data, results from previous interlaboratory trials of fire test methods are reviewed in Table 7 of Paper IV.

Comparing the precision data of the interlaboratory trial of the SAFIR project to earlier studies for fire test methods, the repeatability and reproducibility of the FTIR analysis of smoke gases can be regarded as satisfactory. The effect of fire test inaccuracies included in the variation of FTIR results must be noted in the evaluation.

4.4 Wooden facades in multi-storey houses

The intermediate and large-scale fire tests of wooden facades presented in Paper V aimed at laying a foundation for the reform of structural fire safety regulations related to wooden multi-storey houses. Two different fire scenarios were defined to examine the behaviour of wooden facades: an external fire and a flashover of a compartment fire. The former was deemed applicable to sprinklered buildings and the latter to unsprinklered buildings. These fire situations represent the most severe heat attack which the facade is probable to become exposed to in each case. Naturally, the facade of an unpsrinklered building can also be subject to an external fire source, but the extreme case in severity is a post-flashover compartment fire. A flashover in a compartment of a sprinklered building is considered rare, since it can occur only as a result of a failure of the sprinkler system.

4.4.1 Sprinklered houses

In the case of sprinklered houses, the probable ignition source of the facade is external, for example a pile of garbage or construction waste. A more severe fire exposure due to a post-flashover compartment fire is considered improbable, because the sprinklers are assumed to extinguish a room fire in an early phase.

4.4.1.1 Intermediate-scale experiments

On the intermediate scale, 29 fire tests were carried out using various materials, surface treatments and structures. The experiments were performed according to the test procedure described in Section 3.6.1.

The performance of the specimens was assessed on the basis of flame spread on their front surface. The height of the surface material on each specimen was 2.4 m (elevated 0.5 m from the ground level), corresponding approximately to a typical wall height of one storey. Most specimens consisted of one straight wall section without any corners.

Flame spread times to the upper edge of the specimens varied from 6.5 to 13.5 minutes for painted materials. A fire retardant (FR) treatment applied by brushing before painting roughly doubled the flame spread times. The FR treatment used also decreased and delayed the heat release of the specimens as shown in Figure 3 of Paper V. Indications of even more beneficial FR treatments were obtained from tests of FR impregnated materials.

In general, the effectiveness of a FR treatment of a wooden surface depends on the chemical used, the method of application, the absorption properties of the material, and the finishing treatment (e.g. painting) of the surface. These factors also have effects on the long-term durability of the treatment. Therefore, the selection of a suitable FR treatment for a specific use requires careful consideration of the system as a whole.

Three means to delay or stop the propagation of fire in the ventilation cavity of the facade were studied. A simple fire stop made of bent steel sheet interrupting the cavity (see Figure 7 of Paper V) limited the temperatures measured in the upper edge of the intermediate-scale specimens to below 100 °C. The effect on the flame spread time to the upper edge of the specimen on the front surface, however, was only 1–5 minutes. A steel sheet painted with an intumescent fire-retarding paint was slightly more efficient, delaying the arrival of the flame front to the top of the specimen for 5–7 minutes. The best behaviour of the solutions studied was shown by a flame trap consisting of a pile of steel grids: the delay in the flame spread time was at least 20 minutes. The heat release of the specimens was reduced respectively, as illustrated in Figure 9 of Paper V.

The effects of the structural variation of the facade profile were evaluated using cantilevers and oriels (see Figure 10 of Paper V for details). A cantilever depth of 100 mm was not sufficient to interrupt the fire spread. When the cantilever depth was increased to 200 mm, the flame front was restricted below the protrusion. To increase the severity of the test, an internal corner was introduced to the specimen. Despite the thermal feedback of the sidewall, a 200-mm deep cantilever prevented the propagation of fire to the upper part of the specimen. An oriel with a depth of 300 mm notably delayed, but could not prevent, the flame spread to the upper part of the specimen. After the ignition of the upper part, the flame front propagated rapidly on the preheated surface. When the fire load was reduced by making the lower surface of the oriel of steel sheets, the fire spread was halted by the protrusion.

The heat flux from the flames of burning wood to the facade surface was estimated on the basis of the intermediate-scale tests. Data on average flame spread velocities (V_{ave}) and flame heights ($x_{f,ave}$) were used for calculating a characteristic ignition time $t_{ig,ch}$ as follows:

$$t_{ig,ch} = \frac{x_{f,ave}}{V_{ave}} \tag{18}$$

The flame spread velocities were based on observations at the height range of 1.5–2.0 m where the effect of the burner on the flame spread can be assumed negligible. The flame heights were determined from measured average heat release rates (HRR_{ave}) on the basis of the flame height correlation

$$x_{f,ave}\,(\mathrm{cm}) \approx 0.28 \cdot \mathrm{HRR}_{ave}\,(\mathrm{kW}) + 8 \tag{19}$$

determined specifically for the test arrangement. The characteristic ignition times were compared to a comprehensive collection of cone calorimeter data of different wood products [142], resulting in estimates for irradiance levels. The heat flux of the wall flame was found to be (25 ± 5) kW/m^2, which is consistent with measurements of heat fluxes on walls reported in the literature [23, 143, 144]. Thus, a heat exposure of about 25 kW/m^2 is an appropriate choice for cone calorimeter tests of wood-based products when data for modelling is needed. Furthermore, the information on the heat flux from the flames of a burning material to a surface can be used as input of flame spread models.

4.4.1.2 Large-scale experiments

The large-scale test series for sprinklered houses consisted of six experiments, performed according to the test procedure described in Section 3.6.1. The evaluation of the performance of the specimens was based on flame spread times on the front surface of the facade. Special attention was paid to the flame spread to the lower edge of windows and to the eaves level because these events are crucial for fire spread to the upper-storey compartments or to the attic of the building.

The ventilation cavities of all large-scale facade specimens were partitioned using steel-sheet fire stops at storey boundaries. Even though this kind of fire stop increased the flame spread time to the upper edge of intermediate-scale specimens only marginally (due to the location of the fire stop), the effect would have been more significant on the large-scale specimens. A long, continuous ventilation cavity of a full-scale facade can result in fast fire spread to the eaves level inside the cavity due to the plume effect.

The benefit of FR treatment was clearly observable on the large scale. The flame front reached the upper edge of a two-storey facade without FR treatment in about 40 minutes. On the surface of a similar FR treated specimen, the flame spread stopped before reaching the lower edge of the second-storey window.

The efficiency of 200-mm deep cantilevers in limiting a fire originating from an external ignition source to the first storey of the facade was confirmed in the large-scale test series, in the cases of both a straight wall and an internal corner. However, the importance of the sufficient width of the cantilever was revealed in the tests. In a test of a three-storey facade with 200 mm deep and 2000 mm wide cantilevers below windows, the flames propagated to the upper edge of the specimen beside the windows, detouring the ends of the cantilevers.

A comparison between the intermediate and large-scale experiments was made by predicting the large-scale flame spread times on the basis of the intermediate-scale results. The estimates were based on extrapolation of flame spread rates observed at the upper parts of the intermediate-scale specimens, assuming a constant flame spread rate. Predictions for the maximum heat flux incident on the second-storey window were obtained by presuming the progress of fire to continue unchanged on the second storey of the facade.

The results are presented in Table 7 of Paper V. The measured heat flux maxima were considerably lower than the predicted values. The consistency seems to be better for the flame spread times, the observations being a few minutes longer than the estimates. For both quantities, the estimates are on the safe side of the experimental results. The number of specimens in this approximate extrapolation is limited, but the results suggest that intermediate-scale test results can be used in predicting the large-scale behaviour of wooden facades.

4.4.2 Unsprinklered houses

In the case of an unsprinklered building, in addition to an external ignition source, the possibility of a flashover of a compartment fire must be taken into consideration. The heat attack of a post-flashover fire on the facade is severe, leading to ignition of combustible materials in a few seconds over a large area above the opening of the fire room.

With the post-flashover fire used in the experiments of Paper V, the heat exposure to the facade at the height of the first-storey window above the fire room is in the order of 70 kW/m^2. The test series included five experiments for examining the spread of fire on the facade surface. The test arrangements are described in Section 3.6.1.

The surface temperature of the facade reached the ignition temperature of wood above the fire room opening in 10–40 seconds. A 400-mm deep cantilever above the opening delayed the ignition of wood by only about 3 minutes. Such a short delay does not improve the fire safety of upper-storey compartments. According to the literature, the depth of a horizontal projection or a flame deflector above the fire room opening should be approximately 1 m to adequately protect the upper storeys from fire spread [64, 66].

Prevention of fire spread to the attic of a building was studied by testing two different ventilation structures of eaves shown in Figure 19 of Paper V. One of the eaves was made completely of untreated wood whereas the other one had non-combustible boards on the bottom and front surfaces. The “attic” above the wooden eaves ignited approximately 8 minutes after the flashover. The eaves structure with non-combustible boards could delay the fire spread by only about 2.5 minutes longer. Thus, neither of the eaves structures studied can prevent or considerably delay the spread of fire to the attic.

The attempts to restrict fire spread introduced above indicate that the improvement of the fire safety of facades made of combustible materials is not an easy task. In order to find solutions that ensure an adequate fire safety level, take into account the practice of construction work and satisfy architectural demands, careful consideration and product development are required.

The size of the fire room opening has several effects on the development of fire, both inside the fire room and on the facade above the opening. In the test series, a reduction of 60 % in the opening factor (from 0.079 $m^{1/2}$ to 0.032 $m^{1/2}$) by narrowing the window opening (from 3.0 m to 1.2 m) was studied. The decrease of ventilation reduced the gas temperature of the fire room by approximately 200 °C, and the duration of the fully developed fire was doubled (see Figure 21 of Paper V). The average and maximum heat fluxes incident on the first-storey window above the fire room decreased by about 40 % and 65 %, respectively. In the second storey above the fire room, the reduction of the maximum heat flux was approximately 70 %, but the average heat flux during the most intensive 10 minutes of the fire remained the same. The flame spread on the facade surface was notably slower in the case of the reduced compartment ventilation. The flame front reached the upper edge of the three-storey specimen in about 10 minutes after the flashover for the narrow opening compared to approximately 4 minutes for the wide opening.

4.4.3 Principles for acceptance criteria

The ultimate goal of the fire regulations for a building or a part of a building is to ensure safe exit from the building, also from compartments close to the origin of the fire. In the case of a burning facade, the fire spreads fastest to the next compartment through a window since the flame front can propagate on the facade surface. Thus, the flame spread to the lower edge of the window above the fire compartment and the total heat flux to the window pane are critical for fire safety. In addition, falling parts of the facade must be considered in requirements to ensure the safety of evacuation and fire fighting.

As a result of the facade tests on different scales and in different fire scenarios, a proposal of possible acceptance criteria was defined for the specific test arrangements [73]. The criteria for the two fire scenarios, an external ignition source and a post-flashover compartment fire, are presented in Table 6 with the main test characteristics. The former fire situation was deemed applicable to sprinklered buildings and the latter to unsprinklered buildings, representing the most severe heat attack to which the facade is probable to become exposed.

Table 6. Summary of fire scenario characteristics and possible acceptance criteria.

	External ignition source (sprinklered buildings)	**Post-flashover compartment fire (unsprinklered buildings)**
Test characteristics:		
Maximum heat exposure	40 kW/m^2	70 kW/m^2
Burning time of ignition source	max. 30 min	ca. 15 min
Criteria:		
Falling parts	no pieces larger than 0.1 m^2; no flaming droplets to an area > 0.5 m^2	no pieces larger than 0.1 m^2; no flaming droplets to an area > 0.5 m^2
Heat flux *)	≤ 15 kW/m^2, 1st storey window above fire source	≤ 20 kW/m^2, 2nd storey window above fire room
Fire spread	no farther than to lower edge of window of 1st storey above fire source	no fire spread to eaves level **)

*) The heat flux limit must not be exceeded for longer than 1 minute.

**) Fire spread to the attic must be considered. In addition, fire spread from burning eaves to windows nearby must be restricted.

The proposed criteria include requirements for falling parts, heat flux and fire spread. The basic principles of the criteria are applicable to other facade fire tests, but the numerical values might need revisions for different test arrangements.

The criterion for falling parts is needed because fall-down of large pieces of the facade endanger the safety of occupants exiting the building and fire fighters working to extinguish the fire. In addition, the risk of fire spread due to flaming droplets or particles of the facade material must be considered.

The suggested heat flux limit for the fire scenario of an external fire source is 15 kW/m^2 to the centre of the first-storey window above the origin of fire. This value is close to the critical heat flux of untreated wood products. If the criterion is passed, the ignition of wooden window frames is improbable or at least takes a very long time.

For unsprinklered houses, the suggested heat flux criterion limits the exposure of the second-storey window above the fire room. The heat flux measurement on the first-storey window is prone to large variability due to the presence of strong post-flashover flames. Therefore, the examination of the heat flux to the second-storey window gives more information on the fire spread and the cladding-related endangerment of occupants in upper storeys.

The heat attack of an external ignition source is relatively small outside its vicinity. Consequently, the test method can indicate whether the facade material by itself is capable of spreading the fire. A simple criterion restricting the flame spread below the lower edge of the window in the first storey above the fire source is thus feasible.

The flames of a post-flashover compartment fire cause a severe fire exposure on the facade with effects over its entire height. Since the fire source enhances the fire spread even on the upper part of the facade, the flame spread properties of the facade material are difficult to evaluate. In this scenario, the flame spread criterion can be replaced by the heat flux criterion, because extensive burning of the facade surface causes an increase in heat flux. The propagation of flames to the eaves level, however, must be restricted to avoid further fire spread to compartments nearby or to the attic of the building.

4.5 Fire development in timber construction compartments

A series of fire experiments of timber construction compartments is introduced in Paper VI. The objectives of the study were to determine the temperature development for natural fires inside a room of heavy timber construction, to study the contribution of the timber construction to the fire load, and to evaluate the capability of gypsum plasterboard to protect the timber construction.

The test series included four different timber construction rooms. The experimental arrangement is described in Section 3.6.2.

4.5.1 Gas temperatures

Gas temperatures were measured as averages of five thermocouples at different heights in three locations inside the rooms. The results were compared to the parametric temperature-time curves of the draft for the revised Eurocode 1 (prEN 1991-1-2) [91]. Experimental and calculated gas temperatures are shown in Figures 4 and 16–19 of Paper VI.

The measured gas temperatures in the heavy timber construction room without gypsum plasterboard protection were typically about 700 °C during the most intense burning phase of the movable fire load. Towards the end of the experiment, the gas temperature started to increase. A decay phase with decreasing gas temperatures was not observed. When the heavy laminated timber walls and ceiling of the room were protected by a single layer of gypsum plasterboard, the gas temperature was approximately 800 °C, which is somewhat higher than in the case of the unprotected compartment. Otherwise, the temperature development followed the same pattern.

The reason for the relatively low gas temperatures in these two experiments where the timber surfaces were unprotected or insufficiently protected was the insufficient ventilation. In addition to the movable fire load, considerable amounts of pyrolysis gases were released from the wooden ceiling and walls. Generating and heating up all the volatiles consumed a lot of energy. Due to insufficient supply of oxygen, only a part of the gases could burn inside the compartment. The unburnt gases flowed out of the window opening, causing severe combustion outside the room where oxygen was available. Towards the end of the experiments when most of the movable fire load had burnt, the generation rate of pyrolysis gases decreased allowing more oxygen to enter the compartment. Consequently, the temperature inside the compartment started to increase.

In the experiments of a double-layer gypsum plasterboard protection, the gas temperatures showed maximum values of 1000–1200 °C at about 20–40 minutes after the ignition, both for the lightweight structure and for the heavy timber construction. After that, the gas temperature started to decrease due to the burnout of the movable fire load.

A general problem in the calculation of parametric temperature-time curves is finding appropriate values of thermal properties for the materials of the enclosure boundaries. The thermal properties of many materials are strongly temperature dependent. For calculating the thermal inertia factor of prEN 1991-1-2, the thermal conductivity, density and specific heat of each material involved are needed. In Paper VI, ranges into which these quantities most probably fall were determined as functions of temperature, based on the material data collected by König and Walleij from several sources [107]. From the parameter ranges, the minima and maxima of the thermal inertia factor were calculated as functions of temperature. To obtain single numerical values for the thermal inertia factor, an integral averaging over a temperature range of 20–800 °C was performed for the minima and maxima. The resulting minimum and maximum estimates of the thermal inertia factor were used in the calculations of the parametric temperature-time curves according to prEN 1991-1-2.

In the calculation of the parametric temperature-time curves, only the wooden cribs and the particle board flooring were included in the fire load. In practice, also the walls and the ceiling of the heavy timber construction rooms contributed to the fire when they were not adequately protected by gypsum plasterboard. Inclusion of the walls and the ceiling in the fire load would have resulted in a considerable increase in the calculated duration of the fully developed fire and a slight increase in the predicted maximum temperature. Eventually, however, the model would have become inapplicable due to the burn-through and collapse of the timber structure leading to radically changing ventilation. For safety reasons, it was not possible to continue the experiments until the collapse. Consequently, the calculations were made by excluding the walls and the ceiling from the fire load irrespective of their level of protection, and concentrating on the time period during which the movable fire load and the flooring were intensively burning.

Under the conditions described above, the calculated gas temperatures were 300–500 °C higher than the experimental results during the fully developed fire in the tests where the heavy timber construction was either unprotected or covered by a single layer of gypsum plasterboard.

In the case of the double-layer gypsum plasterboard protection, the agreement of the experimental and predicted gas temperatures was tolerable during the fully developed fire if the parametric curves were calculated using the maximum estimate of the thermal inertia factor, even though the measured temperatures were still below the prediction. In the growth period of the fire, the difference was more considerable since the experimental temperatures increased notably more slowly than the parametric curves.

In conclusion, the parametric temperature-time curves according to prEN 1991-1-2 overestimate the gas temperature development of timber construction compartments, especially when the timber surfaces are unprotected or insufficiently protected from the heat exposure. From the viewpoint of fire safety, however, a more hazardous situation would result from a prediction that underestimates the temperature conditions of the compartment.

Parametric temperature-time curves were originally developed for a so-called standard compartment whose boundaries have thermal properties corresponding to a notional average of masonry, concrete and lightweight concrete. The thermal inertia of timber or gypsum plasterboard deviates considerably from that of the standard compartment. Furthermore, the contribution of the enclosure boundaries on the fire load is not considered in the parametric curves developed for compartments consisting of non-combustible materials.

4.5.2 Energy balance

In Paper VI, energy balance estimations were made for the unprotected and double-layer protected heavy laminated timber rooms to get a comparative picture of the course of events in these experiments.

In a compartment fire, the energy released in combustion is lost by convection due to replacement of hot gases by cold gases, conduction to the compartment boundaries and radiation through openings, or consumed by the release of volatiles from the fuel. These quantities were estimated for the experiments over a time period of 40 minutes, which was the approximate burning time of the movable fire load.

The gas temperatures in the compartments were considered constant, 700 °C in the room without gypsum plasterboard lining and 950 °C in the room with a double-layer gypsum plasterboard protection. The fire load was assumed to consist only of wooden cribs and particle board flooring when the walls and ceiling were covered by gypsum plasterboard, whereas an estimated contribution of timber construction was added in the unprotected case.

The energy balance calculation is summarised in Table 6 of Paper VI. Since several approximations and simplifications were made in the calculations, the results are rough estimates of the terms of the energy balance.

The relatively low gas temperature in the room with unprotected walls and ceiling influences the energy balance in several ways. Firstly, the mass flow rate of incoming air is smaller than in the protected case, resulting in a lower maximum energy release from the fire load. The mass flow rate of gases out of the window opening is larger due to the volatiles from the unprotected timber surfaces, but the related energy loss by convection is still smaller because of smaller temperature difference between the fire room and the ambient. Furthermore, the heat loss to the compartment boundaries and the radiative energy through the window opening are reduced due to the lower gas temperature compared to the room with protected timber surfaces.

Since all experiments in the test series were strongly ventilation controlled because of the relatively large fire load, a considerable amount of pyrolysis gases burnt outside the fire compartment. On the basis of the total energy content of the fuel, it was estimated that the proportion of external burning was approximately 15 % in the case of the protected timber construction, whereas approximately 50 % of the energy release occurred outside the unprotected compartment.

4.5.3 Charring

The char depth and charring rate of timber during a fire influence on the load-bearing capacity of wooden structural elements. In Paper VI, the effects of gypsum plasterboard protection on the charring behaviour of heavy laminated timber walls and ceiling were examined.

Gypsum plasterboard delayed notably the onset of charring. The delay time caused by one layer of gypsum plasterboard (thickness 13 mm) was approximately 20 minutes compared to unprotected surfaces. Using two protective layers (total thickness 28 mm), the delay time was doubled. Similar results have been reported for timber frame assemblies exposed to standard and parametric fires [106].

The charring rate of unprotected timber was of the same order throughout the experiment. A slight reduction of charring rate, however, was observed towards the end of the test. When the timber construction was protected using a double layer of gypsum plasterboard, the charring behaviour was time- and place-dependent. Initially, rapid charring was observed in the ceiling due to a long preheating period before the fall-down of the boards and the high temperature in the compartment at the onset of charring. During the end phase of the test, the charring rate in the ceiling decreased considerably due to the decreasing compartment temperature and the increasing thickness of the char layer protecting the uncharred timber. In the walls, the charring rate was slower and almost constant. It is noted that the gypsum plasterboards remained on the walls throughout the experiment. Even though the boards were dehydrated and cracked, they did not completely lose their protective ability.

The reduction of the heat attack on timber surfaces due to gypsum plasterboard protection was estimated using two methods as explained in Paper VI. The radiative heat flux from the flames incident on the inner surface of the enclosure during the fully developed fire was calculated on the basis of gas temperature inside the compartment. Firstly, the heat flux transferred to the wood through protective layers was estimated by the thermal conduction properties of gypsum plasterboard. Secondly, it was calculated on the basis of the time to onset of charring determined from the measured temperature increase of wood behind gypsum plasterboard. Both methods gave results of the same order. Using a single layer of gypsum plasterboard, the heat flux incident on the wooden surface can be reduced to approximately 10 % of the radiation emitted by hot gases. With a double-layer protection, the heat attack decreases to 3–4 % of the exposure incident on unprotected surfaces.

5. Conclusions

The primary objective of this thesis has been to provide new information on various issues of fire safety assessment of construction products in the context of the harmonized European fire classification system as well as related to more general fire safety aspects. The studies included discuss the prediction of SBI test results using cone calorimeter data, the connections of the Japanese and European fire classification systems of surface linings, smoke gas analysis by FTIR spectrometry, fire safety assessment of wooden facades, and post-flashover fires in timber construction compartments.

A one-dimensional thermal flame spread model can be used to predict the first peak of the heat release rate curve of the SBI test. The early part of the test is of major importance in the determination of FIGRA and the classification of the product tested. The model works reasonably well for products exhibiting minor or moderate lateral flame spread in the SBI test. For these materials, the one-dimensionality of the model can be compensated by the selection of input parameters. In the data set studied, the classification on the basis of FIGRA was predicted correctly for 86 % of the products. With low-ignitability products included to form a special case of the model, 89 % of the class predictions were successful.

An alternative, mathematically simpler means to predict FIGRA values and Euroclasses is a model based on rate of heat release and ignitability indices. The indices can be determined from cone calorimeter data, and an estimate of the FIGRA value can be calculated using a regression equation. This predictive procedure gave correct classification for 80 % of the products studied within its validated ignition time range. If the products without sustained flaming in the cone calorimeter tests are included, the success rate of the class prediction increases to 83 %.

In summary, either of these models can be used for predicting FIGRA values and Euroclasses. However, the type of the product and the limits of validity must be noted before the models are applied. The essential feature of both models is that only the heat release rate data of a single cone calorimeter test ISO 5660-1 at the heat exposure level of 50 kW/m^2 in horizontal orientation is required as input, without a need of any additional data or material parameters. In principle, they can be adapted for input data measured using another heat exposure level or specimen orientation. The models provide practical and economical tools for product development and quality control, thus improving the research and development possibilities of the construction product industry.

The Japanese and European fire classification systems of surface linings have a common reference scenario: a fire in a small room, represented by the ISO 9705 Room/Corner test. The similarities and differences of class definitions can be examined on the basis of the product performance in the reference scenario. However, the Euroclass of a product cannot be directly deduced from its Japanese class or vice versa due to the different fire test methods and parameters used in the classification. For the majority of products, the classification systems are strongly consistent. The inconsistencies can be detected by recognising the materials belonging to the product groups known to be problematic; that is, products consisting of a thin surface layer on a non-combustible medium or high-density substrate, materials igniting after a relatively long heat exposure but producing a notable amount of heat after ignition, and products consisting of an easily ignitable thin surface layer on a well-insulating substrate. The models predicting SBI test results on the basis of cone calorimeter data provide a link between the main fire classification test methods of Europe and Japan.

FTIR spectrometers offer a continuous monitoring technique of several gases simultaneously for smoke gas analysis. The main difficulty in the measurements has been the acquisition of a representative fire gas sample for the analysis. To solve this problem, an optimised sampling system for the fire test environment has been defined and recommendations for sampling procedures have been given. In addition to the FTIR spectrometry, the findings concerning sampling techniques are applicable to all other methods used for the determination of the composition of smoke gases. Recommendations related to data analysis, calibration and software have also been defined. For the verification of the results, the recommendations for sampling and analysis have been applied to fire tests of different types. The responses of the FTIR method and alternative methods, known to be capable of giving reliable results, were compared quantitatively. The precision of the method has been determined in an interlaboratory trial. As a result of the studies, the FTIR analysis of smoke gases has been further developed into an applicable and reliable method for the determination of toxic smoke gas components in fire test conditions. A code of practice for the FTIR method including techniques for sampling, calibration and analysis has been produced.

The fire behaviour of wooden facades in multi-storey houses has been studied in two different fire scenarios: an external fire and a post-flashover compartment fire. In a sprinklered building, a compartment fire is extinguished in an early phase. Thus, the probable reason for the ignition of the facade is an external ignition source. In the case of an unsprinklered building, the possibility of a more severe heat attack due to the flames of a post-flashover compartment fire must be taken into consideration.

In the case of an external ignition source, it was found that the most efficient way to prevent the propagation of fire to upper storeys is the structural modification of the facade profile using cantilevers or oriels. In the design and construction of the protrusion, however, the sufficient depth and width should be considered and non-combustible materials should be used in the lower surface. Another means to limit the flame spread on a wooden facade is fire retardant treatment. It must be noted, however, that the effectiveness of the treatment is dependent on the chemical used, the method of application, the absorption properties of the material, and the finishing treatment of the surface. Furthermore, the long-term durability of various FR treatments should be studied by natural or artificial weathering procedures. However, ageing methods for fire retarded wood products are still undergoing development.

With regard to the use of wood and other combustible materials in the facade, both the proportion and location of these materials must be considered. In any case, a combustible material spreads fire at least in the vertical direction. The rate and extent of the fire spread depend on the fire scenario. If the apartments of the building are sprinklered, few compartment fires become fully developed leading to flames emerging from the window. Thus, combustible products can be used more extensively in the facade than in the case of an unsprinklered building.

Considering the safety of the occupants in the compartments other than the one first ignited, the crucial quantity is the intensity of the fire, which can be evaluated on the basis of the heat flux to the facade. The higher the heat flux, the more easily the fire can spread to other compartments, thus endangering the occupants.

As a result of the experimental study of wooden facades, acceptance criteria for the facades of sprinklered and unsprinklered buildings have been proposed in terms of heat flux, fire spread and falling parts. The principles of the criteria are also applicable to other facade fire scenarios under various test conditions.

Post-flashover gas temperatures and charring behaviour have been studied in fire experiments of timber construction compartments. The contribution of the timber construction to the fire load has been examined, and the protective ability of gypsum plasterboard has been evaluated. The experimental data and observations of this series of full-scale fire tests provide new information on the behaviour of timber constructions in natural fires. The data can be used for estimating time-dependent design fire loads in the case of constructions including combustible materials. The results also provide new evidence on the protective effect of the char layer, resulting in charring rates that reduce through the duration of the exposure of heavy timber structures to the fire.

Gas temperatures measured inside heavy timber construction rooms without adequate protection for the walls and ceiling were relatively low, typically in the range of 600–800 °C. This was due to the ventilation being insufficient in relation to the large amount of pyrolysis gases released both from the movable fire load and the compartment boundaries. Towards the end of the experiment when most of the movable fire load had burnt, the temperature started to increase because the generation rate of pyrolysis gases was decreasing, allowing more oxygen to enter the compartment. In comparison, when the timber construction was protected by a double layer of gypsum plasterboard, the gas temperatures exhibited maximum values of about 1200 °C followed by a decay phase.

Parametric temperature-time curves according to the draft of the revised Eurocode 1 were calculated by assuming that only the wooden cribs and the particle board flooring contribute to the fire load and by concentrating on the time period during which the movable fire load was intensively burning. Under these assumptions, the predicted gas temperatures were found to be approximately 300–500 °C higher than the experimental results for the tests without gypsum plasterboards or with single-layer protection. For the experiments with double-layer protection, the measured temperatures were closer to the calculated values, but the predictions were still on the safe side. The use of parametric temperature-time relationships for timber constructions is not straightforward due to difficulties in selecting appropriate thermal properties for the compartment materials. The parametric curves were originally developed for a compartment whose boundaries have thermal properties corresponding to a notional average of masonry, concrete and lightweight concrete. The thermal inertia of timber or gypsum plasterboard is considerably different. Furthermore, the contribution of the enclosure boundaries on the fire load is not taken into account in the parametric curves developed for compartments consisting of non-combustible materials.

Based on visual observations and rough energy balance considerations, it was estimated that a larger proportion of the pyrolysis gases burnt outside the fire compartment in the case of bare or insufficiently protected timber surfaces compared to protected structures. In the case of protected timber construction, approximately 15 % of the burning took place outside the compartment, whereas the proportion of external burning was approximately 50 % for the unprotected construction. It is important to note that excessive flaming outside a fire compartment leads to an increased risk of fire spread to other compartments and buildings.

Under the natural fire conditions described above, gypsum plasterboard protection delayed significantly the onset of charring of timber constructions. For one layer (13 mm), the delay time of the onset of charring was approximately 20 minutes compared to unprotected timber surfaces. When two layers (making a total of 28 mm) were used, the delay time was doubled. After the fall-down of gypsum plasterboards and the onset of charring, the long-term average of the charring rate was similar to the initially unprotected case. However, when the gypsum plasterboards remained on the walls, the protective effect was not completely lost despite severe dehydration and cracking of the boards.

The overall charring rate was notably reduced if the protective gypsum plasterboard layer remained in its position throughout the most intensive burning period of the movable fire load. After that period, the burning of the ceiling and walls could not maintain the high temperature level inside the room. Due to the decreasing temperature, the heat flux incident on the wooden surfaces was reduced leading to lower charring rates.

Fires in buildings throughout the world kill tens of thousands of people every year. In the industrialized countries, the annual number of fire deaths is typically between 10 and 20 people per million of population, and the number of injuries is roughly tenfold. In addition to human suffering, fire causes considerable property loss and disturbance of normal activities in society. To reduce these losses, fire safety aspects must be continuously taken into account in the design of buildings. Materials and products used in construction work have a significant influence on the fire safety of buildings. Therefore, the fire behaviour of construction products must be evaluated and their use for different purposes must be regulated in order to avoid unacceptable solutions. The studies presented in this thesis hopefully enhance the fire safety assessment of construction products and, together with the many other studies in this field, contribute to the improvement of design of fire-safe buildings.

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Studies on fire safety assessment of construction products

Abstract

Various aspects of assessing the fire safety of construction products related to the initiation and development of fire and the determination of toxic smoke gases have been studied.

Two models for predicting the results of the Single Burning Item (SBI) test have been introduced. The models gave a correct classification for 80–90 % of the products studied. The models provide practical tools for product development and quality control.

The fire test methods and classification parameters of the Japanese and European fire classification systems of surface linings are different. Owing to the common reference scenario, the classification systems are still strongly consistent for the majority of products. Inconsistencies can be recognized by examining the product type and composition and by considering the special features of the main fire tests used in the classification.

An optimised sampling system for smoke gas measurements in the fire test environment using the Fourier transform infrared (FTIR) spectrometry has been defined. Recommendations related to data analysis, calibration and software have been given.

The fire behaviour of wooden facades in multi-storey houses has been studied in two different fire scenarios: an external fire and a post-flashover compartment fire. Acceptance criteria for the facades of sprinklered and unsprinklered buildings have been proposed.

Post-flashover gas temperatures and charring behaviour of timber construction compartments have been studied in large-scale fire experiments. The gas temperature development in the test rooms was found to be dependent on the contribution of wooden enclosure surfaces on the production of pyrolysis gases. The onset of charring of timber structures could be delayed significantly by using sufficient gypsum plasterboard protection.

Keywords

fire safety, fire classification, smoke gases, building materials, ignition, heat release, construction products, models, fire tests, facades, wooden structures, room fires, Euroclasses, cone calorimeter, SBI, FTIR, flame spread, surface linings

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