Fire Properties and Performance

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Contents

17.1 Physical Basics of Fire Performance 912
17.1.1 Fundamental Fire Properties and Performance 912
17.1.2 Fundamental Fire Performance of Wood 913

17.2 Pyrolysis and Combustion of Wood: Chemical Aspects 915
17.2.1 Burning of Wood 915
17.2.2 Flame Retardants 918

17.3 Fire Performance of Wood Products and Structures in Buildings 921
17.3.1 Fire Exposure in Buildings 921
17.3.2 Building Fires with Two Main Stages 921
17.3.3 New Possibilities in Recent Years 922
17.3.4 European System of Fire Safety for Construction Products 922
17.3.5 Reaction to Fire Performance and Classification of Wood Products in Europe 925
17.3.6 Wood Coverings with Fire Protection Ability 929
17.3.7 Reaction to Fire Classification of Wood Products in North America 931
17.3.8 Fire Resistance of Wood Elements 932
17.3.9 Connections 933
17.3.10 Structural Detailing 934
17.3.11 Active Fire Protection of Buildings 935
17.3.12 Performance-Based Design of Buildings 936
17.3.13 Quality Control of Workmanship 938
17.3.14 Fire Safety During Construction 938

17.4 Conclusions 939

References 939

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Abstract

This chapter deals with the fire properties and performance of wood products and structures. It starts with two subchapters on the basic physical and chemical properties under fire conditions including fire-retardant treatments to obtain higher reaction to fire classes. A new European standard to evaluate their long-term fire performance is included. The third subchapter gives an overview of the fire safety design of wood products in buildings. The European system for fire safety of construction products is explained with the two main fire scenarios to be considered: the initial fire where visible wood surfaces may contribute, and the fully developed fire, which is important to limit the fire to the room of origin. Generally speaking, wooden structures can obtain high fire resistance, whereas the surface properties in the initial fire are less favorable. The European reaction to fire class D is fulfilled for most wood products. North American systems are different and their classification of wood products is described briefly. Methods for calculating the fire resistance of wood elements according to Eurocode 5, and US systems, structural detailing, and fire safety at building sites are presented. The chapter ends by explaining the possibilities for using performance-based fire safety design and active fire protection by, for example, sprinklers.

Keywords

Building fires · Charring rate · Fire resistance · Flame retardants · Heat release rate · Ignition · Load-bearing structures · Reaction to fire · Separating structures · Sprinklers

P. Niemz et al. (eds.), *Springer Handbook of Wood Science and Technology*,
https://doi.org/10.1007/978-3-030-81315-4_17

17.1 Physical Basics of Fire Performance

Fundamentals of thermal properties (thermal conductivity, thermal expansion, specific heat capacity, influence of temperature on mechanical properties) are described in ▶ Chap. 6. This chapter describes the physical basics for the fire performance of wood, wood-based materials and wooden constructions.

In comparison with other building materials, such as steel and concrete, wood has a low thermal conductivity, a high specific heat capacity and a low thermal expansion. The influence of temperature on the strength under 100 °C is relatively low (see ▶ Chap. 7). Owing to the low thermal conductivity, the temperature inside the solid wood increases only slightly at fire exposure (see ▶ Chap. 6) (Fig. 17.1). The charcoal layer has an insulating effect and its thickness increases at continued fire exposure. The strength inside the wood is maintained.

17.1.1 Fundamental Fire Properties and Performance

The fire behavior of materials and products is determined by numerous factors. Parameters for characterizing the fire behavior are defined in EN ISO 13943 [2]. Some important definitions related to the **fire performance of materials** are summarized below:

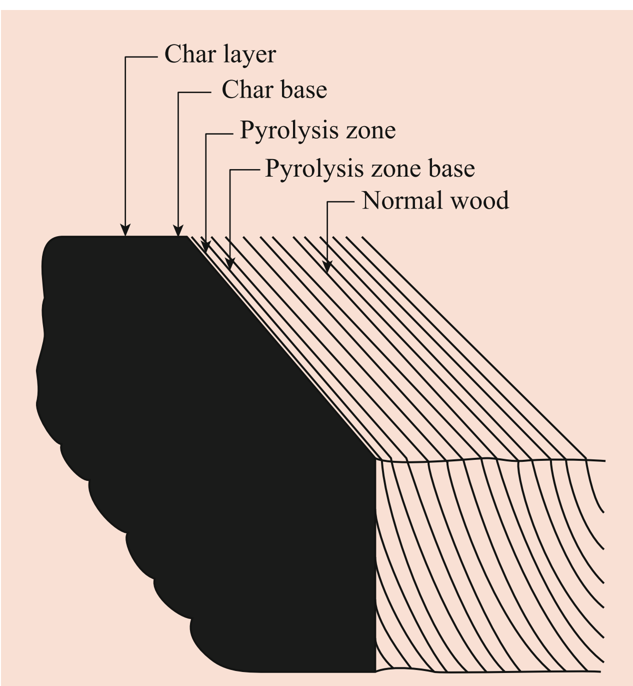


Fig. 17.1 Charring of fire-exposed wood [1]

Afterglow: persistence of glowing combustion after both removal of the ignition source and the cessation of any flaming combustion
Char: carbonaceous residue resulting from pyrolysis or incomplete combustion
Combustion: exothermic reaction of a substance with an oxidizing agent
Effective heat of combustion: heat released from a burning test specimen in a given time interval divided by the mass lost from the specimen in the same time period
Fire retardant: substance added, or a treatment applied, to a material in order to delay or to reduce the rate of combustion
Glowing combustion: combustion of a material in the solid phase without flame but with emission of light from the combustion zone
Heat of combustion: thermal energy produced by combustion of unit mass of a given substance
Heat release rate: rate of thermal energy production generated by combustion
Ignition: initiation of combustion
Ignition time (time to ignition): duration of exposure of a test specimen to a defined ignition source required for initiation of sustained combustion under specified conditions
Improved fire performance: improvement in one or more fire properties of a material, product, or assembly when exposed to a source of heat or flame
Pyrolysis: chemical decomposition of a substance by the action of heat (usually in the absence of oxygen)
Reaction to fire: response of a test specimen when it is exposed to fire under specific conditions in a fire test
Self-heating: rise in temperature in a material resulting from an exothermic reaction within the material
Thermal degradation: process whereby the action of heat or elevated temperature on an item causes a deterioration of one or more properties.

Some other definitions in ISO 13943 are related to the **use of materials in buildings**, e.g.:

Active fire protection: method(s) used to reduce or prevent the spread and effects of fire, heat or smoke by virtue of detection and/or suppression of the fire and which require a certain amount of motion and/or response to be activated
Design fire: quantitative description of assumed fire characteristics within the design fire scenario
Fire performance: response of a material, product or assembly in a fire
Fire resistance: ability of a test specimen to withstand a fire or give protection from it for a period of time
Fire safety design: quantified description of the development of a built environment intended to meet fire safety objectives

Fire safety engineering (FSE): application of engineering methods to the development of a built environment intended to meet fire safety objectives

Fire scenario: qualitative description of the course of a fire with respect to time, identifying key events that characterize the studied fire and differentiate it from other possible fires

Flashover: transition to a state of total surface involvement in a fire of combustible materials within an enclosure

Fully developed fire: state of total involvement of combustible materials in a fire

Load-bearing capacity: criterion by which the ability of a building element or structure to sustain an imposed load when exposed to fire is assessed

Passive fire protection: method to use or prevent the spread and effects of fire, heat or smoke by means of design and/or the appropriate use of material and requiring detection and/or activation upon detection

Performance-based design: design that is engineered to achieve specified objectives and performance criteria

Separating element: physical barrier intended to resist the passage of fire from one side of the barrier to the other side.

17.1.2 Fundamental Fire Performance of Wood

Wood is combustible and can be described as a porous, carbon-forming solid. Its pyrolysis at fire is a very complicated process [3–12]. Wood burns indirectly, which means that the combustion takes place as a reaction between oxygen and the gases released from the solid wood material. At heat exposure wood easily produces substances that react eagerly with oxygen, leading to a high propensity of wood to ignite and burn. These aspects are described in Sect. 17.2.

Although wood is a combustible material, wooden structures can have very good fire performance properties. The reason is that the char layer reduces heat transfer and protects the underlying wood. The dimensions of the wood are also important. Larger dimensions mean that the fire resistance of the wooden structure can be higher. The fire performance depends on the charring rate of the wood and on the reduced strength and stiffness that might occur at extended fire exposure. The thickness of the layer with reduced strength is time-dependent, thin during the early fire stage and up to about 40 mm in the fully developed fire.

The load-bearing capacity of a wooden structural element at fire exposure depends on its strength and rigidity and on the joints between the elements. Both the elements and the connections must fulfill their function during the intended time. The connections can be sensitive to fire exposure, a strategy can therefore be to ensure that the connections have higher fire resistance than the individual elements.

The behavior of metal fasteners depends on the temperature of the metal, which may affect the strength of the fastener itself. High temperatures can lead to charring or loss of wood strength upon contact with a hot metal. Metal conducts heat much better than wood, metal fasteners can therefore conduct heat from outer to inner layers. Steel connection components can collapse relatively quickly in the event of fire, as the modulus of elasticity and strength of steel decrease at high temperatures and the outer layers of the wooden elements can char.

An overview of fire behavior and fire protection in timber buildings from a Russian perspective is published [13].

Some characteristics of fire exposed wood are described in the following sections [14].

Ignitability

The ignition of a wood product is dependent on the way of heating, the thermal properties of the material, and the way in which heat attacks the material.

The factors affecting the ignition of wood are well known in general: wet wood is difficult to ignite, thin pieces of wood ignite more easily than thick logs, and light wood species ignite quicker than heavy species. External factors that have an influence on ignition are the intensity of heat exposure, e.g., the distance of flames from the surface and the presence of flames (piloted ignition) or not (nonpiloted ignition).

The moisture content of wood has an effect on ignition mainly as a heat sink. Heating-up of the water, and especially its vaporization, consumes heat energy. In addition, moisture increases the thermal inertia of the material.

The ignition of wood products with different thicknesses is dependent on their thermal thickness. A thermally thin layer ignites more quickly than a thermally thick material. When a thermally thin product is exposed to heat on one side, its opposite side heats up very close to the temperature of the exposed side by the time to ignition. For a thermally thick product, the opposite side does not heat up but remains at the ambient temperature when the specimen ignites. The thermal thicknesses of practical products fall between thermally thin and thick. As a rule of thumb, a wooden product is thermally thin if its thickness is not more than a few millimeters, and thermally thick if its thickness is of the order of 10 mm or more. Thermally thick wood products are most common in practical building applications and their time to ignition with a pilot flame may vary between 200 and 50 s at constant heat irradiation between 30 and 50 kW/m^2 [1].

The dependence of the time to ignition t_{ig} (s) on the internal properties of a material under radiative heat exposure can be described as follows:

17

$$t_{ig} = \rho c L_0 \frac{(T_{ig} - T_0)}{\dot{q}''_{net}} \qquad \text{for a thermally thin product}$$

$$t_{ig} = \frac{\pi}{4} \rho c k \frac{(T_{ig} - T_0)^2}{\dot{q}''^{\,2}_{net}} \qquad \text{for a thermally thick product}$$

where ρ, c, and k are the density (kg/m^3), specific heat (J/(kg·K)) and thermal conductivity (W/(m·K)) of the material respectively, L_0 is the specimen thickness (mm), T_{ig} is the ignition temperature (K), T_0 is the ambient temperature (K), and $\dot{q}''_{net}$ is the net heat flux to the specimen surface (kW/m^2).

When the thermal thickness of the product is between thermally thin and thick, the exponent describing the effect of the net heat flux $\dot{q}''_{net}$ and the temperature difference $T_{ig} - T_0$ is between 1 and 2.

Self-ignition can occur with shavings, grinding dust due to the action of microorganisms or oxidation of resins and extractives. The temperature is highly dependent on the particle size, the moisture content of the wood, and the pressure to which the particles in the pile are exposed, i.e., the volume of stored particles [15].

Self-heating and risk of auto-ignition may also occur because of the absorption of moisture from the surrounding air by dry low-density bales of hygroscopic cellulosic materials, e.g., insulating fiberboard during storage [16]. Charring may start inside a pile and flaming starts when the char front has reached the surface and gets access to oxygen.

Heat of Combustion

The heat of combustion is the heat energy that is generated by the oxidation reactions of fuels. There is a distinction between the gross heat of combustion (H_o) and the net heat of combustion (H_u). The net heat of combustion is the released thermal energy, reduced by the heat of vaporization (V) of the released water. The following therefore applies:

$$H_o - V = H_u$$

H_o – Gross heat of combustion
H_u – Net heat of combustion
V – Heat of vaporization

The heat of combustion can be calculated directly from the chemical composition of wood. It depends mainly on the relative amounts of the wood components cellulose, lignin, and extractives having different contributions. Typical heat of combustion values for wood products including wood-based panels are 18–21 MJ/kg [17, 18].

Heat Release Rate

Heat released in combustion is the driving force of a fire: the greater the heat released by a burning object, the faster the fire spreads and the hotter the gases and the surfaces of the fire enclosure become. Thus, one of the most essential quantities describing the burning of materials is the heat release rate, denoted with $\dot{Q}$ and expressed in kilowatts or megawatts.

Oxygen consumption calorimetry is used to determine the heat release of materials and is based on the fact that a more or less constant net amount of heat is released per unit mass of oxygen consumed for complete combustion [18]. The general discovery was published by Thornton in 1917 [19] and applied to fire research by Huggett [20] and Parker [21] in the late 1970s. It has formed the basis for a new era in fire research and has been used extensively in experiments, standards, and modeling.

In addition to the internal structure and properties of a material, the heat release rate is strongly dependent on external factors. Therefore, exact $\dot{Q}$ values for different materials cannot be given. The most important external factors having an effect on $\dot{Q}$ are the net heat flux $\dot{q}''_{net}$ to the surface and the oxygen concentration of the ambient air, described with the factor $f(O_2)$. The internal properties of a material affecting $\dot{Q}$ are the heat of combustion ΔH_c, the heat of gasification L_v, and the specific heat capacity C. The following equation shows the heat release rate per unit area of a burning material (A_{burn}):

$$\dot{Q}'' = \frac{\dot{Q}}{A_{\text{burn}}} = \dot{q}''_{\text{net}} \cdot f(O_2) \cdot \frac{\Delta H_c}{L_v + C(T_{ig} - T_0)}$$

where T_{ig} is the ignition temperature (K) and T_0 is the ambient temperature (K). It is noted that, in addition to the incoming heat flux on the surface, $\dot{q}''_{net}$ (kW/m^2) is also dependent on the heat losses from the surface.

The heat release rate per unit area $\dot{Q}''$ can be measured, for example, using the cone calorimeter [22], which describes burning in a well ventilated environment (the early stage of a fire). The results obtained describe the heat release properties of materials, although they are to some extent dependent on the heat exposure level used in the test, the properties of the exposed surface (in the case of wood, e.g., grains, knots, and tendency to crack), and the specimen thickness.

When wood burns, flames spread on its surface. Flame spread can be regarded as a sequence of ignitions. Therefore, flame spread is governed by the same factors as ignition. The heat released by a burning area has an effect on flame spread rate, directly by the flames and through the warming-up of the fire enclosure. Thus, the factors governing the heat release rate are also essential for the flame spread.

Charring Rate

The charring rate is a physical property that depends, among other things, on the density of the wood, the moisture content, and the direction of the fibers. The charring rate usually varies between 0.5 and 2 mm/min. The influence of wood

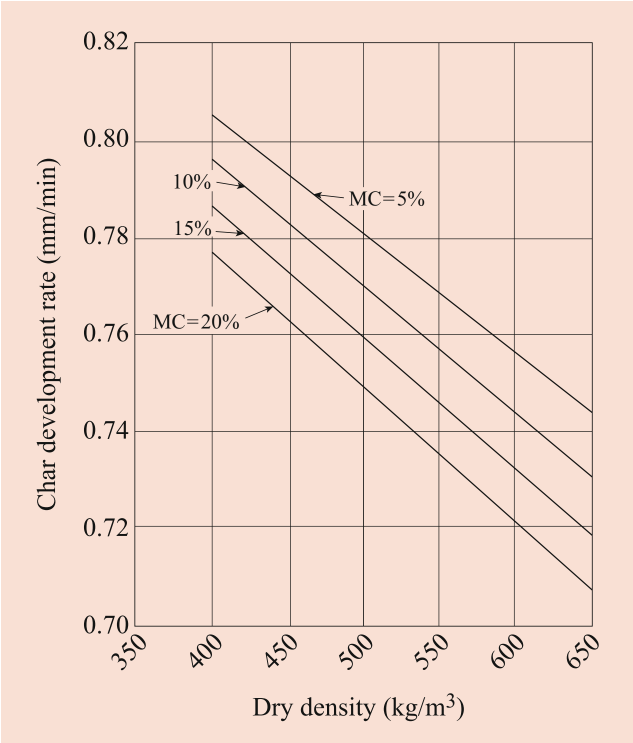


Fig. 17.2 Charring of wood with different density and moisture content (MC) [10]

density and moisture content on charring rate was carefully investigated by Schaffer [10] (Fig. 17.2).

At standard fire exposure, wood chars at a constant rate after the ignition phase and the boundary between the pyrolyzed and the intact wood, i.e., the pyrolysis front, proceeds in the direction of depth. Charring rate is an essential quantity for the fire resistance of wooden structures, because the wood under the char layer preserves its original properties. Typical charring rates transverse grain, which is the most common case in practical applications are 0.5–0.7 mm/min for both softwood and hardwoods at standard fire exposure, slightly dependent on density and wood species [1].

Important factors for the charring rate of wood are the density ρ, the external heat flux $\dot{q}''_{ext}$, and the moisture content w^i [27]. The charring rate decreases with increasing density according to the power law $\beta \propto \rho^{-\upsilon}$, where υ is between 0.5 and 1 ($\upsilon = 0.5$ results from studying only heat transfer and $\upsilon = 1$ corresponds to a model covering only the conservation of mass). The charring rate increases linearly with the external heat flux, $\beta \propto \dot{q}''_{ext}$. An approximate relationship between charring rate and moisture content is $\beta \propto (1 + 2.5w)^{-1}$.

Design values of the charring rate for various wood products are given in Eurocode 5 [23, 24] (Table 17.1).

The charring rate is not generally much influenced by fire retardants [25]. However, the char yield is usually increased quite a lot, which might contribute to the protection of the wood core. Protective coatings may generally be efficient in preventing ignition and the charring of wood, see 17.2.2 and 17.3.5.

Table 17.1 Design charring rates for wood products [23]. Symbols: ρ_k, characteristic density; β_0, design charring rate for one-dimensional charring under standard fire exposure

Product	β_0 (mm/min)
Softwood and beech:	
glued-laminated timber with $\rho_k \geq 290$ kg/m^3	0.65
Solid timber $\rho_k \geq 290$ kg/m^3	
Hardwood:	
Solid or glued-laminated hardwood with $\rho_k = 290$ kg/m^3	0.65
Solid or glued-laminated hardwood with $\rho_k \geq 450$ kg/m^3	0.50

For more information, see, for example, Östman et al., EN 1995-1-2, Klippel, and Klippel and Schmid [3, 23, 26, 27]

17

17.2 Pyrolysis and Combustion of Wood: Chemical Aspects

17.2.1 Burning of Wood

Burning of wood involves two principle processes: pyrolysis and combustion. *Pyrolysis* denotes the thermal decomposition of wood in the absence of, or in limited amounts of oxygen [28]. Pyrolysis proceeds between about 225 °C and 500 °C [29], yielding gaseous and solid compounds. Not wood itself, but the volatile, flammable gasses released out of the wood into the surrounding atmosphere burn in the presence of oxygen and a source of ignition. This process is called *flaming combustion*. Low-density wood species ignite more quickly than high-density species. The solid pyrolysis product, which remains on the surface of the burned wood, is called *char*. Oxidation of the char produces *smoldering* or *glowing combustion*. Smoldering combustion releases noncombustible or unoxidized volatile products (smoke) and is typical of low-density wood species. Wood produces less smoke than many plastics [14]. Decomposition of wood during pyrolysis also produces *tar*. When isolated, tars are black viscous liquids that consist of various pyrolytic degradation products of lignin and carbohydrates (e.g., levoglucosan).

During heating up to approx. 100 °C or higher (depending on the heating rate), wood dries by evaporation of moisture (water, which is not produced by dehydration of wood material) without significant chemical changes. Volatile extractives might also evaporate such as mono- and sesquiterpenes from resinous softwoods (see ▶ Chap. 5). Until about 200 °C, very little decomposition occurs with most gases formed being noncombustible. Between 160 °C and

200 °C, water released through dehydration of the cell wall polymers makes up the majority of the gases. The main pyrolysis of wood takes place between 225 °C and 500 °C (Table 17.2).

Table 17.2 and Fig. 17.3 show the thermal decomposition of wood and its individual constituents during thermogravimetric analysis (TGA) in the absence of oxygen (pyrolyses) and the respective approximate onset and main decomposition temperatures. The temperature ranges for specific decomposition events depend of the wood species and on the heating rate. The *thermal decomposition of whole wood* starts at 225–250 °C and culminates in the highest rate at 390–420 °C, which significantly slows down at increasing temperatures. Above approximately 500 °C, pyrolysis is complete. The char yield amounts to 20–25 % of the initial wood mass and hardly decreases at increasing temperatures up to 800 °C owing to the formation of thermostable graphitic carbon.

Table 17.2 Temperature ranges of wood pyrolysis and combustion. (Adapted from Rowell, and Lowden and Hull [28, 29]

Temperature range	Decomposition processes
Up to about 100–130 °C	Evaporation of moisture (chemically unbound water) and volatile extractives
160–200 °C	The cell wall polymers begin to decompose slowly. Gases formed are noncombustible (mainly H_2O)
200–225 °C	Decomposition of cell wall polymers is still slow, and most of the gases produced are noncombustible
225–275 °C	The main pyrolysis begins and flaming combustion will occur with the aid of a pilot flame
275–500 °C	Gases produced are volatile (CO, CO_2, methane, etc.) and smoke particles are visible. Char forms rapidly as the physical structure of wood breaks down
390–420 °C	Highest decomposition rate of wood
>500 °C	Volatile production is complete. Char continues to smolder and oxidize to form CO, CO_2, and H_2O

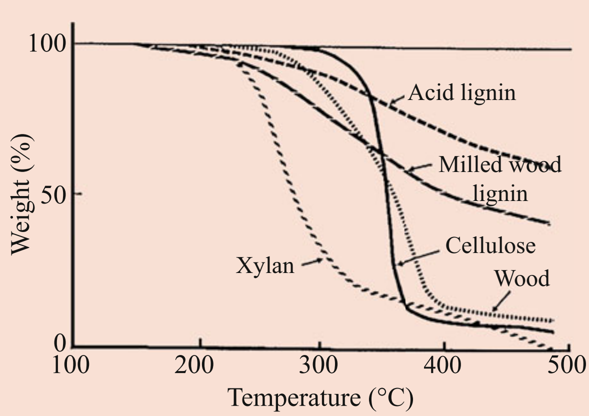


Fig. 17.3 Themogravimetric analysis of cottonwood and its cell-wall components [31]

The TGA decomposition curve of wood represents the superposition of the decomposition process of the individual cell wall polymers (and other constituents in the case of high extractive content). The *hemicelluloses*, such as xylan, exhibit the fastest degradation of all wood polymers. Xylan is almost completely decomposed by about 325 °C, whereas the more stable cellulose starts degradation at about 370 °C, decomposing within a small temperature range. Acid *lignin* and milled wood lignin begin to decompose at a somewhat lower temperature than the carbohydrates at about 200 °C but are much more stable to thermal degradation than these. The main decomposition of lignin occurs around 400 °C. The weight loss of lignin up to 700 °C does not exceed 50% [30] (Table 17.3).

In the first phase of pyrolysis, the cell-wall polymers decompose by the breaking of chemical bonds, dehydration (cleavage of chemically bound water, i.e., reaction water), as well as formation of free radicals, carbonyl, carboxyl, and hydroperoxide groups (primary reactions). Dehydration, decarbonylation, and decarboxylation give rise to gaseous water, carbon monoxide, and carbon dioxide, which leave wood through its porous structure. These gases are *nonflammable* and noncondensable. In addition, *flammable* volatile organic compounds are released that contribute to combustion such as methanol, methane, formaldehyde, acetic acid, acetaldehyde, propenal, butanedione, furfural, etc. Below 300 °C, the majority of these compounds are released from hemicelluloses owing to their low thermal stability.

Reactive (e.g., radical) primary decomposition products undergo further recombination reactions (secondary reactions) either close to the site of their formation in the solid phase (yielding char) or in the gas phase (yielding tar). Most of the primary cleavage products leave the wood as an aerosol – a colloidal system of gases and finely distributed solid and liquid parts. Char is the solid pyrolytic product of wood deprived from hydrogen and oxygen, released mostly as water (dehydration) but also as CO and CO_2. With increasing temperature, its carbon content increases, and graphitic structures are formed. Tar is a liquid pyrolytic product consisting

Table 17.3 Onset and decomposition temperatures of wood and its cell-wall polymers. [28]

Compound	Onset temperature (°C)	Decomposition temperature (°C)
Whole wood	225	400
Cellulose	230	370
Xylan	225	325
Lignin	200	>800

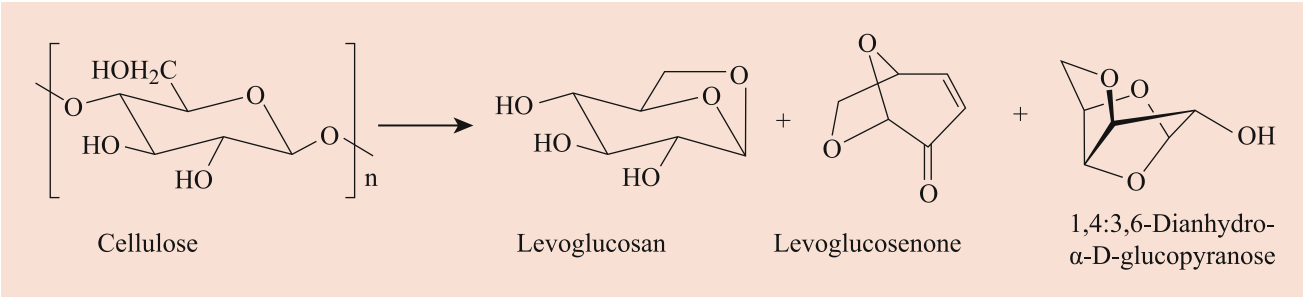


Fig. 17.4 Formation of anhydromonosaccharides due to transglycosylation of cellulose [31]

of volatile low-molecular-weight compounds, in which oligomeric and polymeric products are partly dissolved.

Above 300 °C, cellulose, as the major cell wall polymer, determines the chemistry of pyrolysis and, together with the hemicelluloses, makes the major contribution to volatile production and, thus, flaming combustion. Cellulose's cleavage reactions yield primarily anhydromonosaccharides (Fig. 17.5a), mainly levoglucosan (1,6-anhydro-β-D-glucopyranose) and other monomers, formed by intermolecular and intramolecular transglycosylation of carbohydrates (Fig. 17.4) [32].

These compounds are typical components of cellulosic tar. They are assumed to undergo two simultaneous reaction pathways during pyrolysis [32]: degradation into volatile *low-molecular weight-products* (Fig.17.5b) and *ring-opening polymerization into polysaccharides*. These polysaccharides may de-polymerize back to anhydromonosaccharides (Fig.17.5c) or be successively converted to the solid carbonized (char) products with increasing carbon and decreasing oxygen and hydrogen content (Fig.17.5d). The char yield of cellulose decreases with increasing temperature above 300 °C, whereas the tar yield increases up to about 325 °C and remains more or less constant at higher temperature [31]. At around 500 °C, the carbonized char products begin to form aromatic structures and in further processes – together with lignin-derived char – graphitic carbon structures [29]. In the presence of oxygen, the anhydromonosaccharides (levoglucosan) might also burn directly under flaming combustion after evaporation from the solid phase. The predicted boiling point of levoglucosan is 385 °C [33].

Examples of *low-molecular-weight products*, which derive from levoglucosan decomposition, are levoglucosenone (Fig.17.4), furfural, 5-methylfurfural, and 2,3-butanedione (Fig.17.6).

Decomposition of lignin produces predominantly aromatic tar compounds such as aromatic hydrocarbons, phenolics, hydroxyphenolics, and guaiacyl-/syringyl-type compounds, which may repolymerize to yield carbonized, i.e., O- and H-reduced, char products [34, 35]. These polymerizations might involve radical coupling or reaction

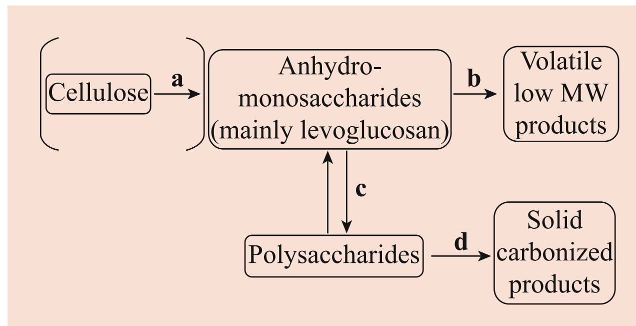


Fig. 17.5 Proposed pathways of cellulose pyrolysis via anhydromonosaccharide-s. MW - molecular-weight. (Adapted from Kawamoto et al. [32])

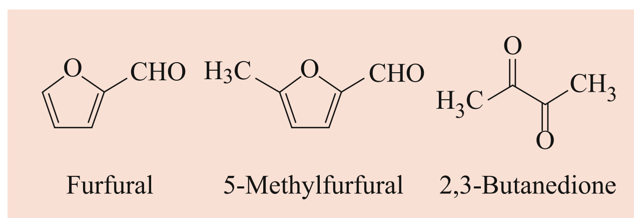


Fig. 17.6 Some volatile low-molecular-weight degradation products of levoglucosan

with tar components deriving from carbohydrates (e.g., levoglucosan).

Owing to its higher thermal stability than for polysaccharides, lignin makes a major contribution to the formation of char and tar. The char yield of lignin after pyrolysis is approximately 50–60 %, whereas that of cellulose is only about 15% (e.g., [28, 31]). In reverse, cellulose and hemicelluloses undergo stronger thermal decomposition resulting mostly in volatile pyrolysis products that are responsible for flaming combustion [36]. It was found that cellulose yields about twice as much in amounts of combustible volatiles as lignin (Table 17.4) [28].

The heat released by flaming combustion is transferred back into the wood, increasing its pyrolysis rate and thus

Table 17.4 Heat of combustion, char and combustible volatile yields of wood, cellulose, and lignin[a]. [28]

	Heat of combustion (ΔH, 20°C, KJ g^{-1})	Char yield (%)	Combustible volatiles (%)
Wood (poplar)	−19.335	21.7	78.3
Cellulose	−17.346	14.9	85.1
Lignin (Douglas fir)	−26.674	59.0	41.0

[a]Heating rate 200°C min^{-1} to 400°C min^{-1} and held for 10 min

propagating the fire. Char formation (and, thus, a higher lignin content in wood) reduces combustion, i.e., the flammability of wood, because it thermally isolates the solid phase (reduced heat transfer) and slows down the pyrolysis process. It also forms a barrier for diffusion of combustible gases and oxygen.

17.2.2 Flame Retardants

Flame retardants are chemical compounds or formulations that stop the spread of fire and flames on the surface of a substrate and decrease the fire intensity. Another aim of using flame retardants is to minimize the production of smoke and toxic gases such as carbon monoxide.

There are three main processes to treat wood with flame retardants:

1. Full-cell treatment via vacuum-pressure impregnation in a pressure chamber mainly with aqueous solutions or dispersions of the flame retardant as usually done for preservative treatment (see ► Chap. 15). This process is predominantly applied for timber but is also possible for veneer-based products (plywood, laminated veneer lumber). Treatment of the latter products can involve individual treatment of the veneers prior to gluing or treatment of the whole panel
2. Surface treatment by dipping, spraying, brush or roll application. Compared with the full cell treatment, the penetration depth of the flame retardant is about 1 mm or less. The formulations applied may be intumescent coatings or nonfilm-forming substances similar to those used in full cell treatment [14]
3. Addition during the production process. Flame retardants are sprayed onto particles, fibers or strands before, after, or together with the adhesive and subsequently pressed to wood-based panels. This may result in significant strength loss compared with panels without added flame retardants, particularly when these are acidic. Surface properties may be inferior with respect to coating or application of laminates

The retentions of flame retardants in wood products obtained in a full-cell process is usually much higher than those of wood preservatives and are often within a range of approximately 5–15%, depending on the type and amount of flame retardant.

The aim of flame retardants used for wood is to delay the ignition and to reduce the heat released during combustion [37]. The various flame retardants may be classified into five types related to their underlying mechanism [28].

1. Changing the pathway of pyrolysis
2. Coating formation on the wood surface
3. Slowing down ignition and burning by changing the thermal properties of wood
4. Reducing combustion by diluting pyrolysis gases
5. Reducing combustion by free radical trapping in the flame

The most effective flame retardants for wood reduce fuel production by increasing the char production and lowering the amount of combustible gases [28]. Therefore, most of the flame retardants used for wood fall under mechanism 1. Most flame retardants, however, operate by several of these mechanisms.

Changing the Pyrolysis of Wood

These substances enhance the pyrolysis reaction of cellulose, which consequently starts at a lower temperature than without flame retardants. This shifts the decomposition of cellulose to produce more char, more water and other inflammable gases at the expense of the flammable pyrolysis products. Most of these flame retardants are either acids or act acidic upon thermal decomposition. Although these types of flame retardants enhance char production, they generally do not influence the charring rate of wood, which is approximately 0.5–1 mm/min [25].

The flame retardants catalyze the acidic hydrolysis and dehydration of cellulose and inhibit the formation of anhydromonosaccharides (mostly levoglucosan). They may react with the hydroxyl group at C6 of the cellulose molecule leading to the formation of a double bond via either dehydration or esterification (Table 17.5) [14]. Double bond formation at C6 disables transglycosylation and thus formation of levoglucosan. Flame retardants may also enhance the condensation of the char to produce thermally stable polycyclic aromatic structures [32]. However, flame retardants appear to have very little effect on the thermal decomposition of lignin [28].

Some flame retardants may also slow down the pyrolysis reactions by stabilizing the chemical structures of the cell wall polymers. As an example, aluminum sulphate prevents thermal decomposition by creating bonds between cellulose molecules at increased temperatures [14].

For a long time, both phosphorous and boron compounds have been the most important chemical compounds for wood (acting according to mechanism 1). Phosphorous compounds still play the greatest role with respect to flame retardancy of timber and wood-based products. Boron compounds, in contrast, are currently losing their importance owing to health concerns (classified as toxic for reproduction) and are likely to be banned in the future.

The predominant mode of action of *boron compounds* (Table 17.6) relies on the acid-catalyzed dehydration of wood polysaccharides. Mixtures of borax and boric acid can additionally form glassy films at a rather low melting point, which may inhibit the transport of combustible gases [38]. Although borax tends to reduce flame spread, it may promote smoldering or glowing. Boric acid, in contrast, suppresses smoldering but does not reduce flame spread. That is why these compounds are usually mixed [38].

Three main groups of *phosphorus flame retardants* are available: inorganic, organic, and halogen containing compounds (Tables 17.7 and 17.8). Inorganic phosphorus flame retardants are red phosphorous (not used for wood), phosphoric acid and ammonium phosphates; ammonium polyphosphate (APP) is the most frequently used inorganic phosphorus compound for wood. Inorganic and organic phosphates typically act in the solid wood phase by forming polymeric phosphoric acid upon heating. This acid causes the formation of a char layer owing to hydrolysis and dehydration [39]. Phosphorous compounds also reduce after-glowing [14].

Some halogen-free phosphorus flame retardants may also quench radicals formed in the gas phase (mechanism 5, see below). Halogenated (chlorinated, brominated) flame retardants act in the gas phase (see below) independently from phosphorous components. When combined, they act additively [39]. Halogen-containing phosphorous compounds, however, do not play a role as flame retardants for wood products.

The most important phosphorous flame retardants are *nitrogen-based compounds*. These involve the inorganic ammonium phosphates mono-ammonium phosphate (MAP), diammonium phosphate (DAP), APP (Table 17.7) and the organic phosphorus compounds containing melamine, guanidine or guanylurea (Table 17.8). Nitrogen-based compounds act synergistically with phosphorus-containing fire retardants to enhance their function. Another type of flame retardants are phosphonates.

Irrespective of the phosphorous moiety, nitrogen-based flame retardants offer various modes of protection [29]. One is that they dilute flammable gasses (mechanism 4) by endothermic decomposition (mechanism 3) into nitrogen-containing compounds, mainly ammonia (Fig. 17.7).

In addition, nitrogen-based compounds may cross-link the wood polymers and, in the case of the organic compounds, form a nitrogen-containing char layer through condensation of decomposition products such as melem, melam, and melon.

Owing to their acidic pH, some phosphorus flame retardants may cause severe strength reduction over time, as shown for MAP used to protect plywood roof sheathing [40]. MAP, DAP, and shorter chain APP are soluble in water and will be leached out during outdoor exposure, see 17.3.5. In contrast, many long-chain APP may exhibit a better outdoor performance because of their low water solubility (< 0.1 g per 100 ml). Particularly MAP and DAP but

Table 17.5 Reaction mechanism of flame retardants at C6 of the anhydroglucose unit in cellulose [14]

Reaction 1 (dehydration)	Reaction 2 (esterification)
$R_2-CH-(CH_2-OH)+H^+\rightarrow$	$R_2-CH-(CH_2-OH)+H_3PO_4\rightarrow$
$R_2-CH-(CH_2-OH_2^+)\rightarrow$	$R_2-CH-(CH_2-O-PO(OH)_2)+H_2O\rightarrow$
$R_2-CH-(CH_2^+)+H_2O\rightarrow$	$R_2-C=(CH_2)+H_3PO_4+H_2O$
$R_2-C=(CH_2)+H^++H_2O$	

Table 17.6 Boron compounds and combinations used as flame retardant for wood [14]

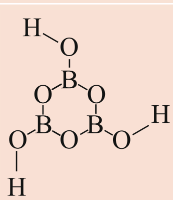
Chemical formula		Name
H_3BO_3		Boric acid
$(HBO_2)_x$		Metaboric acid
B_2O_3		Boron trioxide
$Na_2B_4O_7$•x H_2O		Sodium tetraborate x-hydrate
$Na_2[B_4O_5(OH)_4]$•8 H_2O		Borax
$Na_2B_4O_7+H_3BO_3$		Sodium tetraborate + boric acid
$Na_2[B_4O_5(OH)_4]$•8 $H_2O+H_3BO_3$		Borax + boric acid

Table 17.7 Inorganic phosphorous compounds used as flame retardants for wood

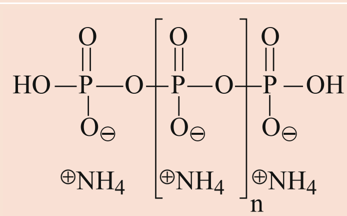
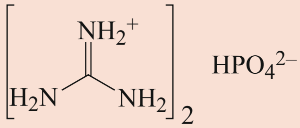
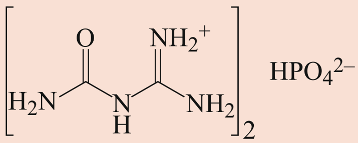
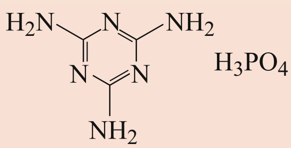
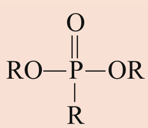
Chemical formula		Name
H_3PO_4		(Ortho) phosphoric acid
$(NH_4)H_2PO_4$ (NH_6PO_4)		(Mono) ammonium (dihydrogen) phosphate
$(NH_4)_2HPO_4$ $(N_2H_9PO_4)$		Diammonium (hydrogen) phosphate
$[NH_4\ PO_3]_n(OH)_2$		Ammonium polyphosphates

Table 17.8 Organic phosphorous compounds used as flame retardants for wood

Chemical formula	Name
	Guanidine phosphate
	Guanylurea phosphate
	Melamine (mono) phosphate
	Phosphonates

$$(NH_4)_2HPO_4 \longrightarrow NH_3 + NH_4H_2PO_4 \quad (155\ ^\circ C)$$
$$NH_4H_2PO_4 \longrightarrow NH_3 + H_3PO_4$$
$$2H_3PO_4 \longrightarrow H_2O + H_4P_2O_7 \quad (170\ ^\circ C)$$
$$H_4P_2O_7 \longrightarrow 2H_2O + P_2O_5$$

Fig. 17.7 Thermal decomposition of diammonium phosphate [29]

also APP are hygroscopic and may increase the moisture content of treated timber and thus enhance the risk of fungal infection.

A more recent approach to enhancing fire performance is the calcination of wood, which results in the deposition of calcium carbonate ($CaCO_3$) in the wood matrix [41]. The modified wood exhibited reduced formation of volatiles and enhanced char yields (mechanism 1). $CaCO_3$ in the cell lumen and the cell wall may also act as a barrier (mechanism 2) and release noncombustible gases such as water (from the hydrated minerals) and carbon dioxide in an endothermic process (mechanism 3) diluting pyrolysis gases (mechanism 4).

Coating Formation on the Wood Surface

Flame retardants of this type form a physical barrier (char) on the wood surface, which prevents the flammable products from evaporation and oxygen from reaching the substrate. They also isolate the substrate from high temperatures. Most of these coatings are intumescent. *Intumescent coatings* expand when exposed to heat. They form a porous, carbon-rich layer. A disadvantage of these coatings is that they are opaque (nontransparent).

Intumescent coatings contain substances that:

1. Form char: typically, carbohydrates (e.g., sucrose or starch) or polyhydric alcohols
2. Enhance intumescence (blowing agents) such as dicyandiamide, melamine, guanidine, and urea. These compounds form CO_2, H_2O, and NH_3 upon decomposition
3. Enhance dehydration and esterification (phosphates, boron compounds). Blowing agents may also act as a dehydrating agent

Intumescent coatings are only used indoors, mostly with a special topcoat owing to their hygroscopicity and fragility. A typically applied quantity of an intumescent coating is in the range of 500 g m^{-2}, resulting in a thickness of a few hundred micrometers [14].

Expandable Graphite

Expandable graphite produces an intumescent layer of carbon when heated. In its structure, acid, typically sulfuric, is intercalated between the layers of graphite. At around 200 °C, production of nonflammable gas and vapor causes rapid expansion of the graphite layers. At the same time, these gasses dilute the fuel in the gas-phase. Expandable graphite may be applied as nontransparent surface coatings for solid wood and wood-based panels [29].

Other types of physical barrier-forming chemicals are *silicon compounds* such as silicates (water glasses), silica gels, silanes, and silicone. In the presence of heat and oxygen, these compounds form isolating inorganic silica residue. Silicon compounds have also been used to impregnate wood (full-cell treatment), often in combination with boron and phosphorus compounds, partly also with nitrogen compounds [29]. Boron compounds may also form glassy films as a barrier for combustible gasses [38] (see above).

Changing the Thermal Properties of Wood

The thermal properties of wood may be changed by adding components with a high thermal inertia and diffusivity (thermal conductivity) to the substrate. The added components slow down the heating rate of the product and dissipate the heat from the surface. The most commonly used components are metal layers [14].

Another approach is to add chemicals that absorb heat owing to vaporization or endothermic decomposition. Examples are compounds that contain great amounts of water of crystallization or contain chemically bound water such as aluminum hydroxide or borax. Vaporization of the bound water is an endothermic process that consumes heat in the pyrolysis zone, thereby slowing down the pyrolysis. In addition, water has a higher specific heat capacity than dry wood. Thus, wet wood burns poorly because water in wood must be additionally heated up and evaporated. Examples of flame retardants that undergo endothermic decomposition are nitrogen-based compounds.

Reducing Combustion by Diluting Pyrolysis Gases

These flame retardants decompose (partly endothermically) during heating and release noncombustible gases. The dilution of the pyrolysis gases prevents the formation of a flammable mixture of gases and oxygen. It may also inhibit chemical reactions in the flame, resulting in incomplete combustion and reduction of heat to sustain burning. Aluminum hydroxide or borax releases water vapor (see above); ammonium phosphates and other nitrogen-based compounds yield large amounts of CO_2, H_2O, and NH_3, and other noncombustible gases below the temperatures where the main pyrolysis starts.

Reducing Combustion by Free Radical Trapping in the Flame

These flame retardants act as scavengers of highly-reactive free radicals such as H•, OH• and O• in the gas phase by reacting with Cl• or Br• atoms. They do not directly influence the solid phase and do not prevent after-glow [14]. Examples are organohalogen compounds containing bromine and chlorine. These are used in the plastic industry, mostly but not always with a synergist (e.g., antimony trioxide). Organo-halogens, however, are to be avoided for application on wood because they require high retentions (15–30 % by weight) [28] and because of toxicity and environmental aspects. Halogenated, particularly bromine-containing, flame retardants may bioaccumulate in the human body and cause adverse health effects in children (Janssens 2005 cited in Lowden and Hull [29]).

Some phosphorus compounds may also act as radical quenchers in the gas phase (see above).

17.3 Fire Performance of Wood Products and Structures in Buildings

17.3.1 Fire Exposure in Buildings

Building elements are usually designed to resist the so-called standard fire curve according to ISO 834 [42] (Fig. 17.8). This curve has an ever increasing temperature with no decay phase and is used to classify building elements as, for example, load-bearing for 30 min (R 30) or separating for 60 min (EI 60), which are requested in most building regulations.

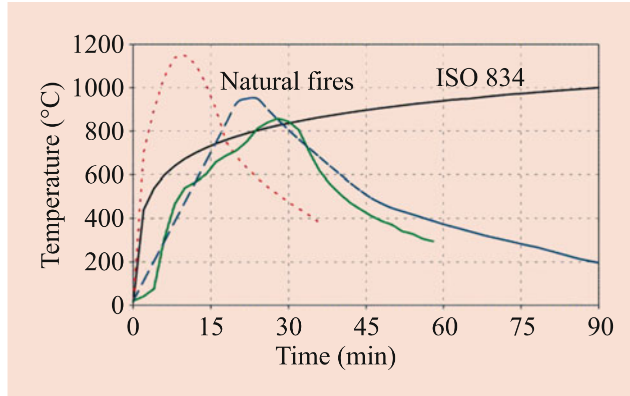


Fig. 17.8 Examples of time–temperature fire exposure curves in buildings

However, real fires can be very different and have always a decay phase. The differences are dependent on the available fuel (building content), the ventilation conditions, the geometry, and the thermal inertia of the compartment.

After ignition, severe fires may grow rapidly, but some grow slowly and will stay at the stage of smoldering combustion until they grow or self-extinguish. Uncontrolled fires reach a stage where all oxygen in the compartment is consumed and further fire development and temperatures in the compartment are governed by the available oxygen inflow, e.g., through windows that normally can resist fire exposure for only a few minutes. Whenever the fire load, normally the movable items, is consumed, the fire decays. Alternative fire exposure curves for structures are given in EN 13501-2 [43]. General design fire scenarios are presented in an international technical specification ISO/TS 16733 [44].

Fire safety engineering can be used to apply scientific and engineering principles to the impact of fire in order to reduce the loss of life and damage to property by quantifying the risks and hazards involved and provide optimal solutions to the application of preventive or protective measures [45].

Recently, several large-scale experimental studies have been performed to determine realistic fire scenarios in wood buildings with different ventilation conditions and different exposed wooden wall and ceiling linings [46, 47]. They may lead to a more realistic view of exposure conditions in building fires for different scenarios.

17.3.2 Building Fires with Two Main Stages

There are two different stages of a fire scenario to be considered in the fire safety design of buildings in relation to building materials and structures [3]. These are the initial and the fully developed fire (Fig. 17.9). In the initial fire,

17

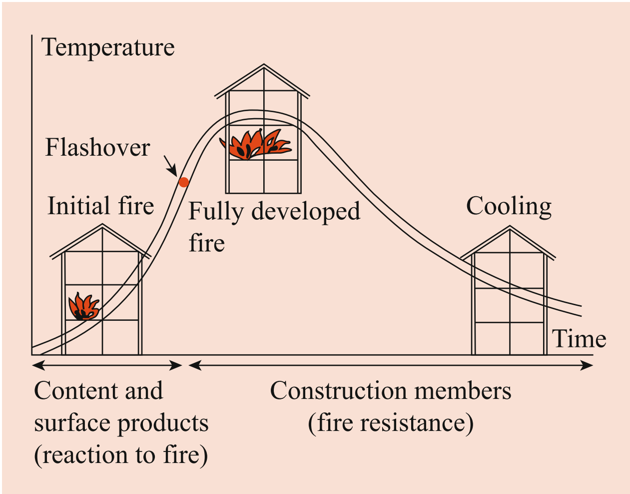


Fig. 17.9 The two main stages relevant to fire safety in buildings in relation to building materials and structures

the building contents e.g., furniture, is of major importance, both for the initiation of the fire and its development, but the building contents are not regulated in building codes. Surface linings may contribute to the initial fire, especially in escape routes, as those are required to have no furniture and furnishings. Limitations of the reaction to fire of surface linings are required in most national building codes. In the fully developed fire, i.e., after flashover in a room, the performance of load-bearing and separating structures is important in order to limit the fire to the room or compartment of fire origin. This is called the fire resistance of the building structure.

Generally speaking, wooden structures can obtain high performance for fire resistance and high levels for the separating and load-bearing capacity of wall and floor structures can be achieved, whereas the surface properties of wooden linings in the initial fire may be less favorable and also more difficult to quantify. The highest levels of the reaction to fire properties cannot be obtained by ordinary wood-based products.

Chemical treatments with fire retardants may reduce or delay the combustion of wood products and usually have the best effects in the initial fire stage. Higher ratings to the reaction to fire performance can then be obtained see 17.2.2. However, in the fully developed fire, such treatments usually have no or limited effects. Important factors for the fire resistance of wooden structures, such as the charring rate, are not usually affected by the treatments [25].

17.3.3 New Possibilities in Recent Years

The combustibility of wood is one of the main reasons why many building regulations strongly restrict the use of wood as a building material. Fire safety is an important contribution to feeling safe, and an important criterion for the choice of materials for buildings. The main precondition for increased use of wood products and structures in buildings is adequate fire safety [3].

World-wide, several research projects on the fire behavior of wooden structures have been conducted over the decades around the millennium, aimed at providing basic data and information on the fire-safe use of wood in buildings. Novel fire design concepts and models have been developed, based on extensive testing and calculations. The current improved knowledge in the area of fire design of wooden structures, combined with technical measures, particularly sprinkler and smoke detection systems, and well-equipped fire services, allow the safe use of wood in a wide field of application. As a result, many countries are revising their fire regulations, thus permitting greater use of wood. Overviews have been presented [48, 49, 50].

Fire test and classification methods have recently been harmonized in Europe, but regulatory requirements applicable to building types and end uses remain on national bases. Although these European standards exist on the *technical level*, fire safety is governed by national legislation, and is thus on the *political level*, but the new European harmonization will hopefully provide means of achieving common European regulations.

The systems for reaction to fire performance of building products are different in other parts of the world. The North American system is presented in Sect. 17.3.7.

17.3.4 European System of Fire Safety for Construction Products

To ensure fire safety in buildings, a European system including product standards, performance classes in case of fire, testing and calculation standards for fire performance has been introduced. The European standards for fire safety in buildings are concerned mainly with harmonized methods for verification of the fire performance.

Building regulations are generally being altered toward functional or performance criteria, rather than being prescriptive. This development was accelerated by the Construction Products Directive (CPD), which was adopted in 1988 and replaced by the Construction Products Regulation (CPR) [51] in 2013. The CPR contains seven essential requirements, one of which is safety in the case of fire. The CPR requirements on fire safety are that structures must be designed and built such that, in case of fire:

- Load-bearing capacity can be assumed to be maintained for a specific period of time
- The generation and spread of fire and smoke are limited
- The spread of fire to neighboring structures is limited

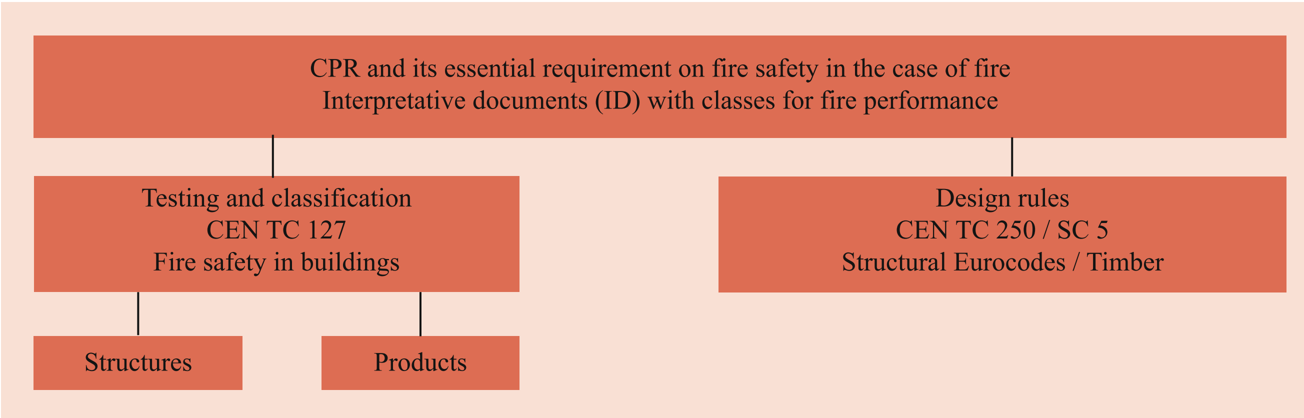


Fig. 17.10 Systems for developing European fire standards for building products [3]

- Occupants can leave the building or be rescued by other means
- The safety of rescue teams is taken into consideration

These essential requirements are implemented and developed by different technical committees (CEN TCs) into European standards (Fig. 17.10).

Reaction to Fire Performance of Building Products

Reaction to fire means the response from materials to an initial fire attack and includes properties such as time to ignition, flame spread, heat release rate, and smoke production (Fig. 17.11). These properties are relevant in early fire development, which is the stage when combustible construction products may contribute to the fire.

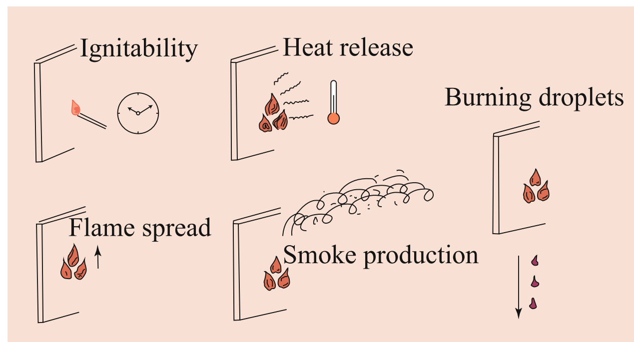


Fig. 17.11 Reaction to fire properties of surface products such as wall and ceiling linings

A European classification system EN 13501-1 [52] for the reaction to fire properties of building construction products was introduced by a European Commission decision in 2000. It is often called the Euroclass system and consists of two sub-systems, one for construction products excluding floorings, i.e., mainly wall and ceiling surface linings (Table 17.9), and another similar system for floorings. Both sub-systems have classes A to F, of which classes A1 and A2 are non-combustible products. This European system has replaced the earlier national classification systems, which have formed obstacles to trade.

The European classification system for reaction to fire performance is based on a set of EN standards for different test methods. Three test methods are used for determining the classes of combustible building products (Table 17.10).

The methods are illustrated in Fig. 17.12. Methods EN ISO 1182 (noncombustibility) and EN ISO 1716 (calorific potential) are also used for noncombustible products, classes A1 and A2.

The European system has to be used for all construction products in order to get the CE mark, which is the official mandatory mark to be used for all construction products on the European market. Different product properties have to be declared and may vary for different products, but the reaction to fire properties are mandatory for all construction products.

Fire Protection Ability

A European system with K classes for the fire protection performance of building panels is defined in EN 13501-2 [43]. The K classes are based on full-scale furnace testing in horizontal orientation according to EN 14135 [56], and the main parameter is the temperature behind the panel after different time intervals (10, 30, and 60 min). No collapse or falling parts are allowed. The test principle is illustrated in Fig. 17.13.

The aim of the K classes is to provide fire protection of underlying parts of a structure, e.g., the insulation in a wall or floor element. Two types of K classes are defined, depending on the substrate behind it. Class $K_1 10$ includes substrates with density less than 300 kg m^{-3}, whereas classes $K_2 10$–$K_2 60$ include all substrates; thus, in practice it is sufficient to verify K_2 classes.

Table 17.9 Overview of the European reaction to fire classes for building products excluding floorings

Euroclass	Smoke class	Burning droplets class	Requirements according to Noncomb	SBI	Small flame	FIGRA W/s	Typical products
A1	–	–	x	–	–	–	Stone, concrete
A2	s1, s2 or s3	d0, d1 or d2	x	x	–	≤120	Gypsum boards (thin paper), mineral wool
B	s1, s2 or s3	d0, d1 or d2	–	x	x	≤120	Gypsum boards (thick paper), fire retardant-treated wood products
C	s1, s2 or s3	d0, d1 or d2	–	x	x	≤250	Coverings on gypsum boards
D	s1, s2 or s3	d0, d1 or d2	–	x	x	≤750	Wood and wood-based panels
E	–	– or d2	–	–	x	–	Some synthetic polymers
F	–	–	–	–	x	–	Not passing class E criteria

SBI, Single Burning Item, main test for the reaction to fire classes for building products, EN 13823
FIGRA, Fire Growth Rate, main parameter for the main fire class according to the SBI test
Noncomb, noncombustibility; W/s, watt-second

Table 17.10 European test methods for the reaction to fire classes of combustible building products

Test method	Construction products excluding floorings	Floorings	Main fire properties measured and used for the classification
Small flame test EN ISO 11925-2	X	X	Flame spread within 60 or 20 s
Single Burning Item test SBI, EN 13823	X	–	FIGRA SMOGRA Flaming droplets or particles
Radiant panel test EN ISO 9239-1	–	X	CHF Smoke production

FIGRA, Fire Growth Rate; SMOGRA, Smoke Growth Rate; CHF, Critical Heat Flux

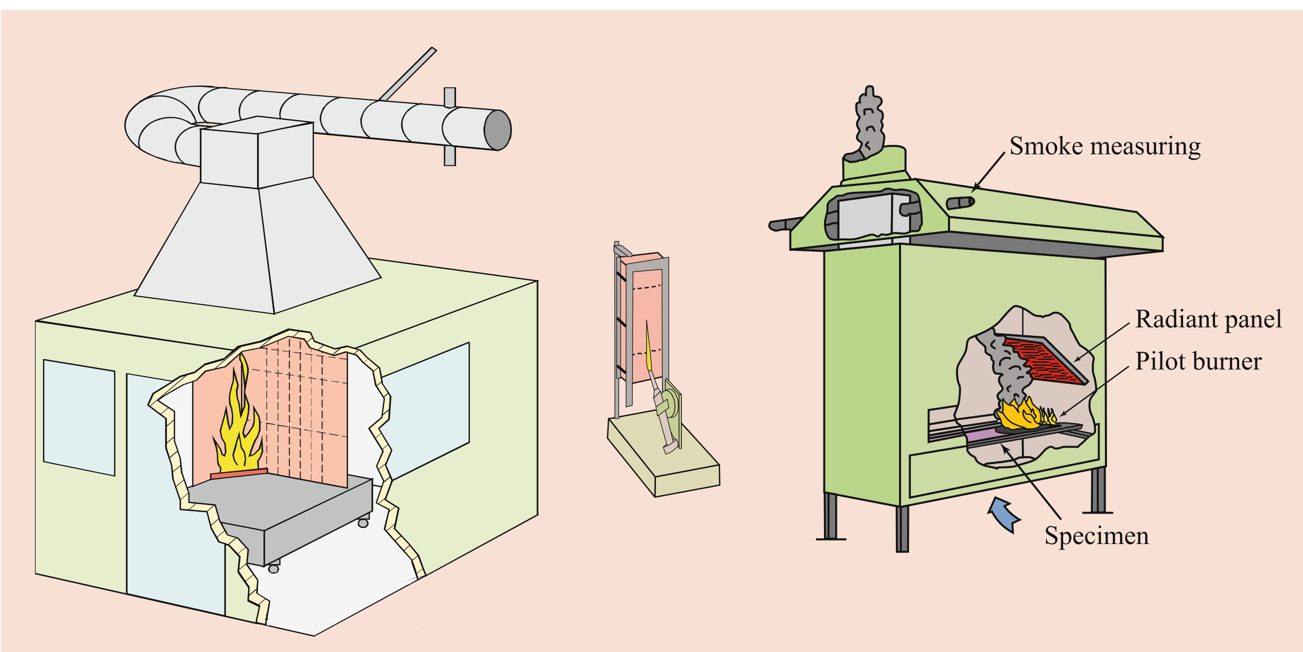


Fig. 17.12 The three main test methods for the reaction-to-fire performance relevant for wood products: the Single Burning Item (SBI) test, EN 13823 [53], Small Flame test EN ISO 11925-2 [54], and the Radiant Panel test for floorings EN ISO 9239-1 [55]

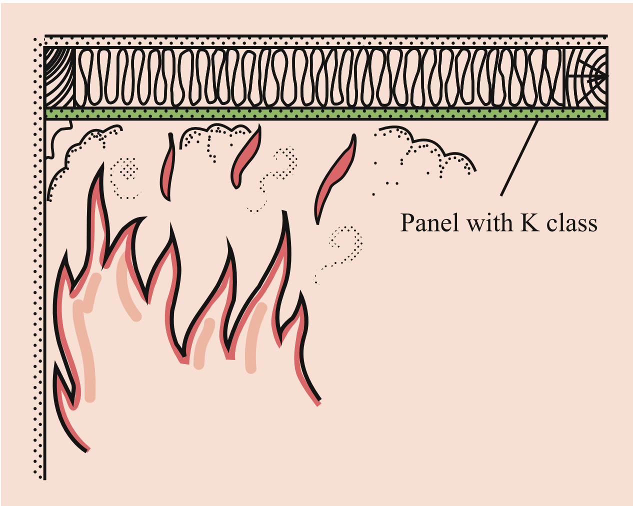


Fig. 17.13 Principle for testing fire protection ability according to EN 14135 [56]

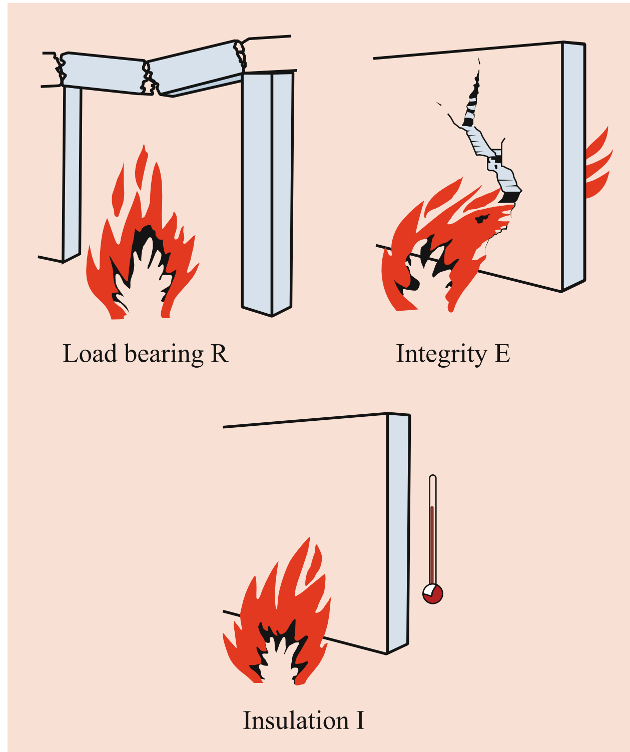


Fig. 17.14 Performance criteria for fire resistance. They are used together with a time value, e.g., REI 60 for an element that maintains its load-bearing and separating functions in 60 min. The criteria apply for both horisontal and vertical elements [3]

Structural Fire Performance: Fire Resistance
Fire resistance means that structural elements, e.g., wall elements, shall withstand a fully developed fire and fulfil requirements of insulation, integrity, and/or load-bearing capacity (Fig. 17.14). Fire resistance can be achieved either by testing according to EN 13501-2 [43] or by calculating according to Eurocode 5 [3, 23].

The fire exposure is usually in accordance with the so-called standard time–temperature curve. This curve is defined in the international standard ISO 834 [42] and referred to in almost all national building codes. It specifies a fire exposure with ever increasing temperatures, which building elements are expected to withstand for a specified period of time, e.g., 60 min. Wooden structures can obtain high fire resistance, e.g., REI 60, REI 90, or even higher.

17.3.5 Reaction to Fire Performance and Classification of Wood Products in Europe

Untreated Wood Products
The reaction to the fire performance of wood products is closely linked to the product density. The fire performance can be expressed as the Fire Growth Rate (FIGRA), which is the main parameter used for the Euroclass system EN 13501-1 [52] and measured by the Single Burning Item (SBI) test EN 13823 [53], see (Fig. 17.15).

Products with known and stable fire performance may be classified in groups according to an initiative from the European Commission [58]. This is a possibility for wood products that have a fairly predictive fire performance.

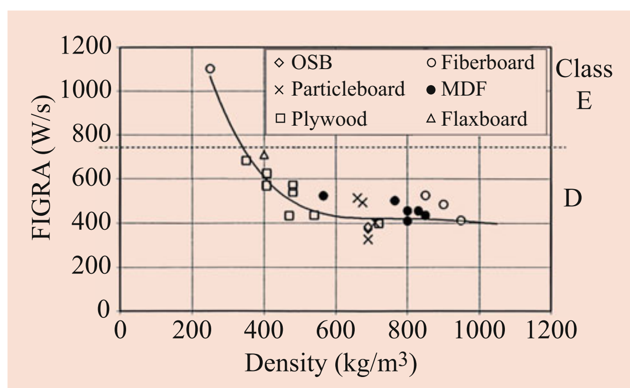


Fig. 17.15 Fire Growth Rate (FIGRA); main parameter used for the Euroclass system) as a function of density for wood-based panels attached to a calcium silicate substrate. Class D is obtained for all products except for a low-density fiberboard [57]

Properties such as density, thickness, joints, and type of end use application may influence the classification. The procedure was called Classification Without Further Testing, and is a list of generic products, not a list of proprietary products. The procedure was later renamed CWT.

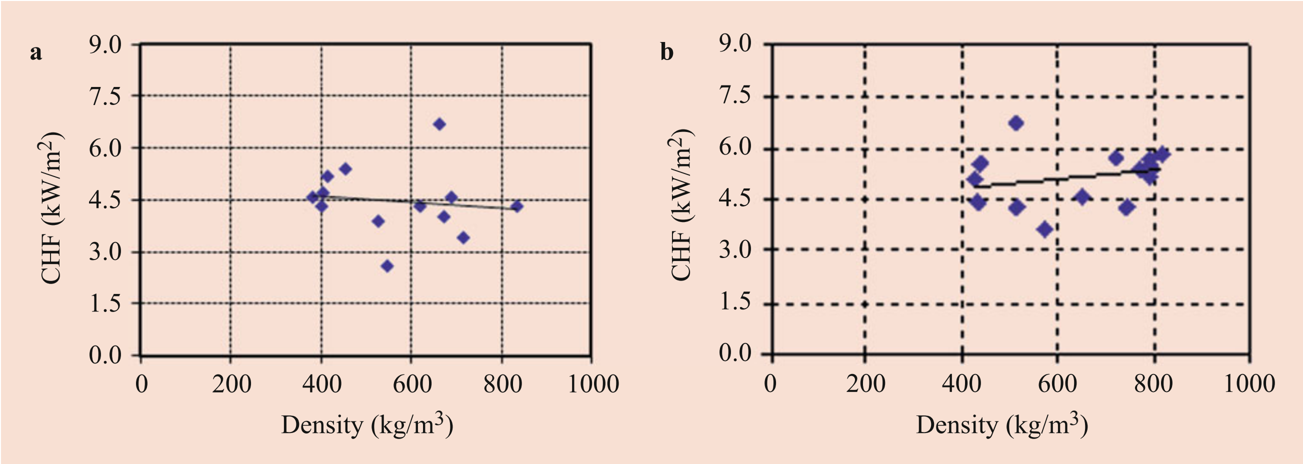


Fig. 17.16 Critical Heat Flux (CHF) for homogeneous floorings (**a**) without and (**b**) with a surface coating [57]

The CWFT/CWT approach has been applied to several types of wood products, e.g., wood-based panels, structural wood, glued-laminated timber, solid-wood paneling, as well as claddings and wood floorings [57–60]. Most of the wood products included fall into classes D-s2, d0 or D_{fl}-s1 (for floorings) (Tables 17.11, 17.12, 17.13).

However, for floorings no clear trend with density has been found [57] (see Fig. 17.16, where six wood species of different origin and thicknesses have been included). Wood floorings show a more rapid flame spread in the orientation along the wood grain than transverse. The orientation along the grain should therefore be used as the worst case scenario. Coating systems improve or at least maintain the fire performance in the Radiant Panel test for floorings. This conclusion was drawn from a systematic study with well-defined uncoated products and coating systems including all major systems used by industry, i.e., ultraviolet-cured acrylic, polyurethane, and oil coating systems used by the parquet industry, as well as ordinary wood oil and soap, which are mainly used for solid wood floorings. The lack of trend with density for the wood floorings may be explained by the much lower heat flux in the testing of floorings than in testing wall and ceiling coverings, which is natural because the heat flux toward floorings is much lower in real fires. This lower heat flux allows gases to be released and influence the flame spread differently for different wood species, depending, for example, on the wood permeability. A coating system may then decrease the release of gases at a low heat flux and thus improve fire performance. The absence of a trend with density is true both for uncoated and for surface-coated homogeneous solid-wood floorings (Fig. 17.16).

Data on fire performance are presented in tables consisting of the reaction to fire classification of different wood products and end-use applications. These tables have been approved by the European Commission and published in their Official Journal [59]. The tables are also included in the relevant harmonized product standards and may be used for CE marking. Further details on the CWFT classification are available in the European guideline [3].

Wood products and end-use applications not included in the CWFT classification tables have to be tested and classified in the ordinary way. Better classification may then be reached, as no safety margins have to be fulfilled.

Fire retardant-treated wood products always have to be tested and classified separately, as the treatments may influence their reaction to fire performance; they may then reach the CE mark.

Fire Retardant-Treated Wood Products

It is relatively easy to improve the fire performance of wood products. Most existing fire retardants are effective in reducing different reaction to fire parameters of wood such as ignitability, heat release, and flame spread. The highest European and national fire classifications for combustible products can be reached [3]. However, high retention levels have to be used compared with ordinary preservation treatments used to protect wood against biological decay. Different types of fire retardants are presented in Sect. 17.2.

Fire retardants may influence the reaction to fire properties, but for the fully developed fire, the influence is minor [25]. One exception is intumescent paints, which may delay the time for the start of charring and thus increase the fire resistance of wooden structures. In any case, fire retardants cannot make wood noncombustible.

However, the excellent fire performance of the virgin fire retardant, FR, means that wood products may degrade over time, especially in outdoor applications. Thus, when exposed to high humidity, the FR chemicals may migrate in the wood toward the surface and may ultimately be leached out. Even at moderate outdoor humidity and indoors, the fire

Table 17.11 Classes of reaction-to-fire performance for wood products except floorings, all without a surface coating [3, 60]

Product (according to product standards as EN 13986 and EN 14915)	End use condition	Min. density (kg/m^3)	Min. thickness (mm)	Class (excluding floorings)
Cement-bonded particleboard (minimum 75 weight % cement)	With or without an air gap behind	1000	10	B-s1, d0
Hardboard	Without an air gap behind the panel	900	6	D-s2, d0
Wood-based panels	Without an air gap behind the panel	600	9	D-s2, d0
	With or without an air gap behind		18	
Solid-wood paneling and cladding	Without an air gap behind	390	12	
	With or without an air gap behind		18	
Wood-based panels	All	600	3	E
Fiberboard, soft		250	9	
Structural timber[a]	With rectangular or round cross sections in accordance with EN 14081	350	22	D-s2, d0
Glued-laminated timber[a]	In accordance with EN 14080	380	40	D-s2, d0
Cross-laminated timber[b]	With or without an air gap behind	350	54[c]	D-s2, d0
Laminated veneer lumber[d]	With or without an air gap behind	400	18	D-s2, d0

[a] Applies to all species covered by the product standards
[b] Minimum cross-laminated timber lamella thickness 18 mm
[c] Minimum total thickness of cross-laminated timber according to the product standard EN 16351
[d] Minimum laminated veneer thickness 3 mm

Table 17.12 Classes of reaction-to-fire performance for surface coated wood floorings [3, 57]

Product[a]	Product detail[b]	Minimum mean density (kg/m^3)	Minimum overall thickness (mm)	End-use condition	Class for floorings
Wood flooring and parquet	Solid flooring of oak or beech	Beech: 680 Oak: 650	8	Glued to substrate[c]	C_{fl}-s1
-"-	Solid flooring of oak, beech or spruce	Beech: 680 Oak: 650 Spruce: 450	20	With or without air gap underneath	C_{fl}-s1
-"-	Solid-wood flooring and not specified above	390	8	Without air gap underneath	D_{fl}-s1
-"-	-"-	390	20	With or without air gap underneath	D_{fl}-s1
Wood parquet	Multilayer parquet with a top layer of oak of at least 5 mm in thickness	650 (top layer)	10	Glued to substrate[4]	C_{fl}-s1
-"-	-"-	650 (top layer)	14[d]	With or without air gap underneath	C_{fl}-s1
-"-	Multilayer parquet and not specified above	500	8	Glued to substrate	D_{fl}-s1
-"-	-"-	500	10	Without air gap underneath	D_{fl}-s1
-"-	-"-	500	14[d]	With or without air gap underneath	D_{fl}-s1
Veneered floor covering	Veneered floor covering	800	6[d]	Without air gap underneath	D_{fl}-s1

[a]Mounted in accordance with EN ISO 9239-1, on a substrate of at least Class D-s2, d0 and with a minimum density of 400 kg/m^3 or with an air gap underneath
[b]Type and quantity of surface coatings included are acrylic, polyurethane, or soap, 50–100 g/m^2, and oil, 20–60 g/m^2
[c]Substrate at least Class A2-s1, d0
[d]An interlayer of at least Class E and with a maximum thickness 3 mm may be included in applications without an air gap, for parquet products with 14 mm thickness or more, and for veneered floor coverings

performance may deteriorate because the FR chemicals migrate away from the surface toward lower concentration regions deeper inside the material thus increasing the flammability of the product (see below).

Durability Classes for Fire Performance

The problems with a maintained reaction to fire performance over time have been known for a long time in the US and the UK, but are not so well known in the rest of Europe. A US study on exterior exposure of North American products over

Table 17.13 Classes of reaction-to-fire performance for noncoated wood floorings [3, 57]

Product[a]	Product detail	Minimum mean density (kg/m^3)	Minimum overall thickness (mm)	End-use condition	Class for floorings
Wood flooring	Solid flooring of spruce	450	14	Without air gap underneath	C_{fl}-s1
Wood flooring	Solid flooring of pine	450	14	-"-	D_{fl}-s1
Wood flooring	Solid flooring of spruce	450	20	With or without air gap underneath	C_{fl}-s1
Wood flooring	Solid flooring of pine	450	20	-"-	D_{fl}-s1
Wood parquet	Solid-wood (one layer) parquet of walnut	650	8	Glued to substrate[b]	C_{fl}-s1
Wood parquet	Solid (one layer) parquet of oak, maple and ash	Ash:650 Maple: 650 Oak: 725	8	-"-	D_{fl}-s1
Wood parquet	Multilayer parquet with oak top layer, at least 3,5 mm	550	15	Without air gap underneath	D_{fl}-s1
Wood flooring and parquet	Solid flooring and parquet not specified above	400		All	E_{fl}
Cross-laminated timber[c]	Surface veneer of Scots pine	430	54[d]	With or without air gap underneath	D_{fl}-s1
-"-	Surface veneer of Norway spruce	400	54[d]	-"-	D_{fl}-s1
Laminated veneer lumber[e]	Surface veneer of Scots pine	480	15	-"-	D_{fl}-s1
-"-	-"-	430	20	-"-	D_{fl}-s1
-"-	Surface veneer of Norway spruce	400	15	-"-	D_{fl}-s1

[a]Mounted in accordance with EN ISO 9239-1, on a substrate of at least Class D-s2, d0 and with a minimum density of 400 kg/m^3 or with an air gap underneath
[b]Substrate at least Class D_{fl}-s1
[c]Minimum cross-laminated timber lamella thickness 18 mm
[d]Minimum total thickness for cross-laminated timber according to the product standard EN 16351
[e]Minimum laminated veneer lumber thickness 3 mm

a 10-year period [61] and a literature review [62] have been published.

Two cases of durability of the fire-retardant treatment of wood products can be identified. One is the risk for high moisture content and migration of the fire-retardant chemicals within the wood product and salt crystallization on the product surface. These hygroscopic properties of the treated wood-based product can be evaluated by exposure to high relative humidity. The other case is the risk for decreased fire performance due to loss of the fire-retardant chemicals by leaching or other mechanisms. This case is mainly for exterior applications, such as façade claddings. Maintained fire performance over time has to be verified.

A European system with Durability of Reaction to Fire performance, DRF, classes EN 16755 [63] has been developed in order to guide the potential users to find suitable FRT wood products:

- DRF class INT1 (interior dry conditions) with no durability requirements
- DRF class INT2 (interior humid conditions) with requirements for limited moisture content
- DRF class EXT (exterior applications) with additional requirements for maintained fire performance after accelerated or natural weathering

EN 16755 will be revised in 2023 and the DRF classes may be modified.

The system is based on a North American system and a previous Nordic system. It consists of a classification system for the properties over time of FRT wood and suitable test procedures (Table 17.14). It provides a useful supplement to requirements for fire performance in national building codes and provides guidance to potential users for finding suitable and reliable FRT wood products.

Fire Performance Before and After Weathering
The fire performance before and after weathering is determined by using predicted time to flashover in a room scenario. This procedure has been chosen in the European approach, as the full-scale test methods referred to in the classification are hard to use for accelerated aging owing to their size. The prediction method [65] is based on the parameters heat release rate and time to ignition in the cone calorimeter, which are correlated with the time to flashover in the room corner test ISO 9705 [66]. The prediction method has been confirmed by later studies.

The reaction to fire performance is reduced after both accelerated ageing and natural field exposure for most FRT products (Fig. 17.18) [67]. All of the FRT products studied lost their improved fire performance after 10 years. The best

Table 17.14 Requirements for Durability of Reaction to Fire (DRF) classes of fire retardant-treated wood products according to EN 16755 [63]

DRF class	Intended use	Fire class Initial	Performance requirements for different end uses	
			Hygroscopic properties	Fire performance after weather exposure
INT 1	Interior, dry applications	Relevant fire class	–	–
INT 2	Interior, humid applications	- " -	Limited moisture content Minimum visible salt	–
EXT	Exterior applications	- " -	- " -	Maintained fire performance

Further details are given in EN 16755 [63]
The relevant initial fire class shall be verified according to EN 13501-1 [51] or International Maritime Organization systems [63]. Maintained fire performance after weather exposure shall be verified according to ISO 5660 [22] (Fig. 17.17), or the European system EN 13501-1

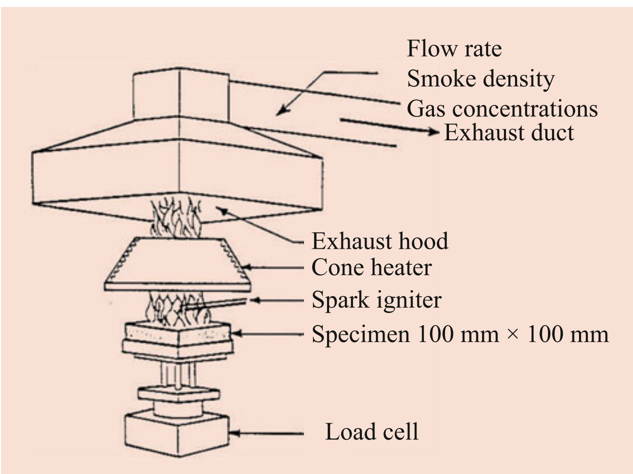


Fig. 17.17 ISO 5660, Cone calorimeter, with a specimen size measuring 100 × 100 mm. Used for product development and for verifying the reaction to fire performance after weathering [22]

performance is found at high retention levels and for FRT products with paint as a protective surface coat. The other FRT products were more or less degraded during the weathering, regardless of whether they had a protective coat or not.

It was also demonstrated that a few FRT products may maintain their improved fire properties up to 5 years, but not for 10 years.

The accelerated ageing thus seems to be equivalent to a maximum of 5 years of natural field exposure. However, it should be noted that the field exposure includes a certain degree of acceleration. The 45° exposure was intended to include some acceleration, but no major difference compared with the vertical (90°) orientations was found. This may be explained by the lack of protection on the rear sides of the vertical panels, which were open to weather exposure. On the other hand, the panels at a 45° slope were at least partly protected on the rear side from the direct influence of rainfall and snow. In a real end use, e.g., as a façade cladding, the rear side is protected. Such conditions have to be studied further before clearer guidance on the accelerating factors can be established.

The mass loss during accelerated ageing and natural weathering has been recorded and it is obvious that it increases with exposure time (Fig. 17.19) [67]. Mass loss may thus be used as a simple indication of fire retardants lost during weathering exposure.

Structural degradation in FRT wood products is described in Sect. 17.3.8.

Conclusions on FRT wood include:

- The system with DRF classes for the long-term fire performance should be implemented, especially for outdoor applications
- Paint systems contribute considerably to weather protection and are usually needed to maintain the reaction to fire performance at exterior applications
- The relationship between accelerated and natural weathering in different climates is not known and should be studied through international cooperation in order to further develop the conditions for accelerated weathering
- Structural degradation of FRT wood used as roof elements may occur, but it is relevant only for load-bearing uses, which are common mainly in North America. In Europe structural uses are not common
- The main safe use of FRT wood is as surface linings in interior applications, e.g., in escape routes, flats in taller residential buildings, public buildings, assembly halls, and sports arenas

17.3.6 Wood Coverings with Fire Protection Ability

The low thermal conductivity and slow charring rate of wood products may protect underlying materials from being heated and ignited. A literature survey shows that such fire-

Fig. 17.18 Reaction to fire performance (as predicted time to flashover) before and after accelerated ageing according to Methods A and B, and after natural weathering at a 45° slope for 1 and 10 years. Untreated spruce (0) and fire retardant-treated spruce (with commercial treatments called BS, DQ, and BH). The first numbers denote different loadings and the last numbers (if any) denote different surface coatings [67]

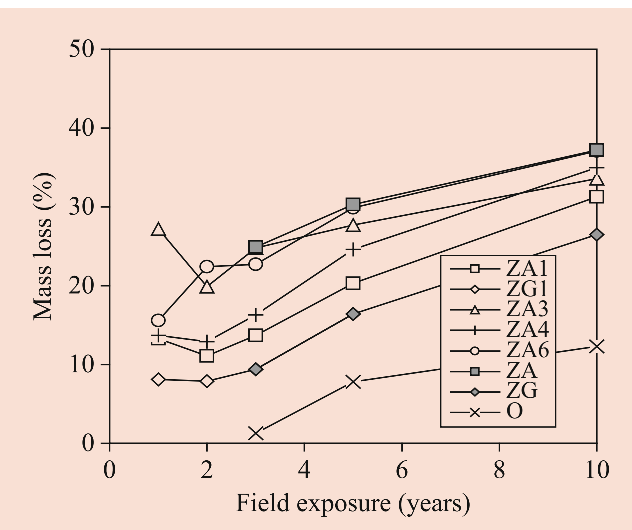


Fig. 17.19 Total mass loss during natural weathering of FRT and untreated wood over a 10-year period [67]

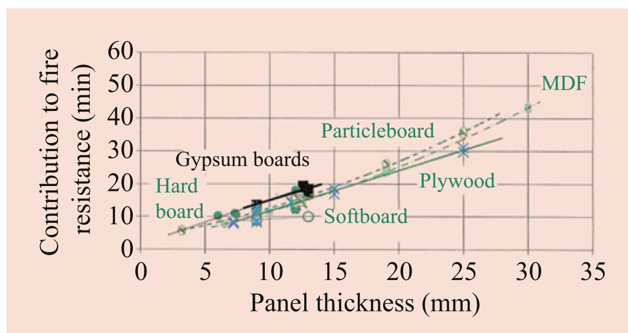


Fig. 17.20 Effect of panel thickness on the contribution to fire resistance of different wood-based panels and gypsum boards [68]

protective behavior of wood coverings has been verified by different methodologies [68] (Fig.17.20). These studies have often been performed to demonstrate the use of component additive methods to calculate the separating fire resistance of wood assemblies [3] and to provide input data to be used for modeling. Eurocode 5 [23] uses the term "basic insulation value," which is closely related to fire protection ability.

Wood-based panels and wood paneling and cladding fulfil the European K classes for fire protection ability. The criteria for the classification of wood products are based mainly on panel thickness. The thickness for achieving each K class may vary slightly, depending on the wood product type and on mounting conditions and means of fixing. Typical thickness to reach 10-min fire protection is 10–15 mm, for 30 min 24–30 mm, and for 60-min protection 52–54 mm (Table 17.15).

The end-use applications of wood products with K classes are mainly as wall and ceiling coverings and for protection of underlying materials and structures. Examples are protection of wooden structures from becoming charred, and protection of steel structures from reaching high temperatures. K

Table 17.15 Wood-based products fulfilling K classes for fire protection ability [3, 70]

K class	Product	CEN standard	Joints	Fixing device Type	Min. length (mm)	Max. spacing at edge (mm)	Min. density (kg/m^3)	Min. thickness (mm)
$K_2$10[a]	Particleboard	EN 13986	Tongue and groove	Screw	30	150	600	10
	-“-	EN 13986	–	Screw	30	200	600	12
	Plywood	EN 13986	–	Screw	30	200	450	12
	Oriented strand board	EN 13986	–	Screw	30	200	600	10
	Hardboard	EN 13986	–	Brad	40	100	800	9
	Solid-wood panel	EN 13986	–	Screw	30	200	450	13
	Solid-wood paneling and cladding	EN 14915	Tongue and groove	Nail	60	600	450	15
	Cross-laminated timber[b]	EN 16351	–[c]	Screw	75	200	450	54[d]
	Laminated veneer lumber[e]	EN 14374	–[c]	Screw	30	200	450	15
$K_2$30	Particleboard	EN 13986	Tongue and groove	Screw	50	200	600	25
	Plywood	EN 13986	-“-	Screw	50	200	450	24
	Oriented strand board	EN 13986	-“-	Screw	50	200	600	30
	Solid-wood panel	EN 13986	-“-	Screw	50	200	450	26
	Solid-wood paneling and cladding	EN 14915	-“-	Nail	60	600	450	27
	Laminated veneer lumber[e]	EN 14374	-“-[c]	Screw	30	200	450	26
$K_2$60	Solid wood panel	EN 13986	Tongue and groove	Screw	75	200	450	52
	Solid-wood paneling and cladding	EN 14915	-“-	Nail	60 In each layer	600	450	2 x 27
	Cross-laminated timber[b]	EN 16351	-“-[c]	Screw	75	200	450	54[d]
	Laminated veneer lumber[e]	EN 14374	-“-[c]	Screw	75	200	450	52

[a]Also fulfills $K_1$10 for substrates with density ≥300 kg/m^3 behind the cladding
[b]Minimum cross-laminated timber lamella thickness 18 mm
[c]Same thickness as wood product without joint
[d]Minimum total thickness of cross-laminated timber according to the product standard EN 16351
[e]Minimum laminated veneer lumber thickness 3 mm

classification is required by building regulations in some countries, e.g., Germany, Denmark, and Sweden.

The ability to use wood-based products as thermal barriers was recognized in the US as early as the 1980s [69], but does not seem to have been implemented in structural fire design.

17.3.7 Reaction to Fire Classification of Wood Products in North America

The North American system for reaction to fire classification of building products is based mainly on the so-called 25-ft tunnel test, which is specified by both the American Society for Testing and Materials and the National Fire Protection Association [1]. Two parameters are derived from the test results: the Flame Spread Index and the Smoke Developed Index. The limits for the three classes A, B, and C specified are given in the International Building Code IBC (international within the US; Table 17.16). The table presents the classification for typical wood products. It is obvious that the class is determined only by the Flame Spread Index and that most wood products fall into class C.

No system for the fire classification of wood floorings is used in the US.

17

Table 17.16 Flame spread classes for interior surface finishes according to US norms

Flame spread class	FSI	Typical wood products (FSI)	SDI	Wood products (SDI)
A	0–25	Only fire retardant-treated products	0–450	All
B	26–75	A few softwood species	0–450	All
C	76–200	Most US wood species	0–450	All

FSI, Flame Spread Index; SDI, Smoke Developed Index

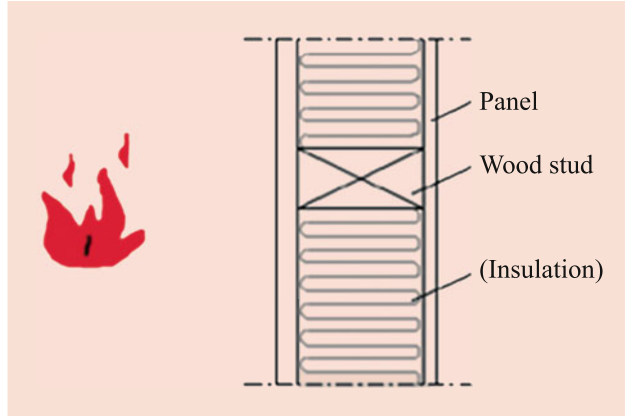


Fig. 17.21 Example of a wood frame wall structure, for which the fire resistance can be calculated using the component-additive method

17.3.8 Fire Resistance of Wood Elements

Separating Structures

The fire resistance for separating structures includes verification of the E and I performance criteria (Fig. 17.14). Separating structures are used to limit the spread of fire from one fire cell, e.g., from one compartment, to another. A simple and practical method for calculating the fire resistance is available in Eurocode 5 [3, 23]. The total fire resistance of an assembly is calculated as the sum of the contribution to the fire resistance from each layer of material (see equation below). This component-additive method also takes into account where the layer of material is located in relation to the fire exposure by so-called coefficients of position (see Fig. 17.21).

The following equation is used:

$$b_{tot} = b_1\,k_1 + b_2\,k_2 + \ldots = \Sigma b_n\,k_n\,[\min]$$

where

b_{tot}: total fire resistance of the construction
$b_n k_n$: fire resistance of the individual layer in the construction
b_n: basic value of fire resistance for the layer of material
k_n: coefficient of position depends on the location of material in relation to fire exposure

An improved calculation method with more flexibility is available in handbooks [3] and will be introduced in the next version of Eurocode [23].

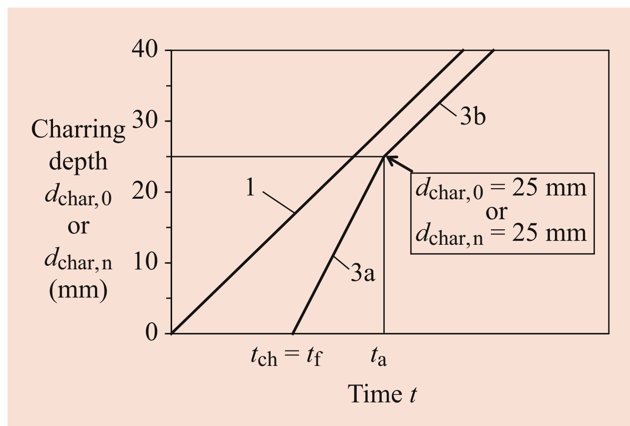


Fig. 17.22 Charring depth versus time when charring starts at the time of failure ($t_{ch} = t_f$) [3]. **1** Relationship for members unprotected throughout the time of fire exposure for charring rate β_n (or β_0). **3a**, **3b** Relationship for initially protected members after failure of the fire protection. **3a** After the fire protection has fallen off, charring starts at an increased rate. **3b** After the char depth exceeds 25 mm, the charring rate falls to the rate for initially unprotected members

Load-Bearing Structures

The fire resistance of load-bearing assemblies means fulfilling the R performance criterion (Fig. 17.14), combined with a number symbolizing the minutes of fire resistance under standard fire exposure [3]. Usually, steps of 15 or 30 min are used. The time of fire resistance of load-bearing elements is strongly related to the applied load. In general, failure of fire-exposed members occurs earlier, the higher the load, and thus the closer the applied load to the maximum load-bearing capacity of a member at normal temperature. This means, that the fire resistance of, for example, a load-bearing glulam beam of a certain dimension may be, for example, R 60 or R 30 depending on the applied load.

The essential verification of the load-bearing capacity can be done by means of calculations, tests, or a combination of both. In Europe, the design follows Eurocode design methods [23]. Eurocode as well as other available design standards use the charring rate as the main parameter to determine the load-bearing capacity after a distinct time of fire exposure (Fig. 17.22). Charring depth versus time when charring starts at the time of failure ($t_{ch} = t_f$) [3].

Further information on the design of separating and load-bearing timber structures are given in Östman et al. [3, 82].

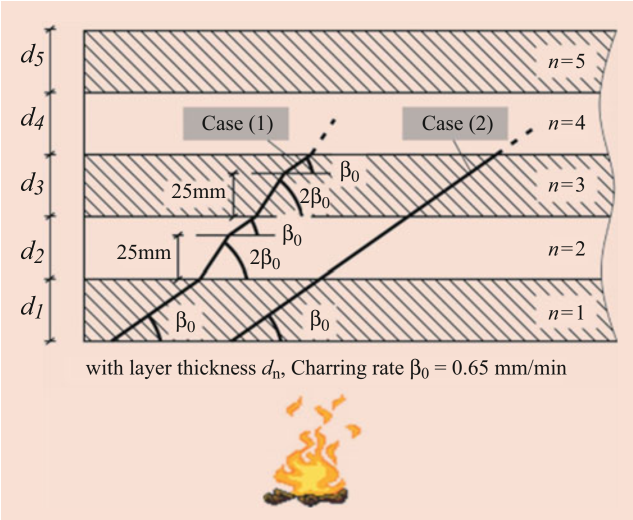


Fig. 17.23 Charring with and without delamination of charred layers. ([27], reprinted by permission of Taylor & Francis Ltd.)

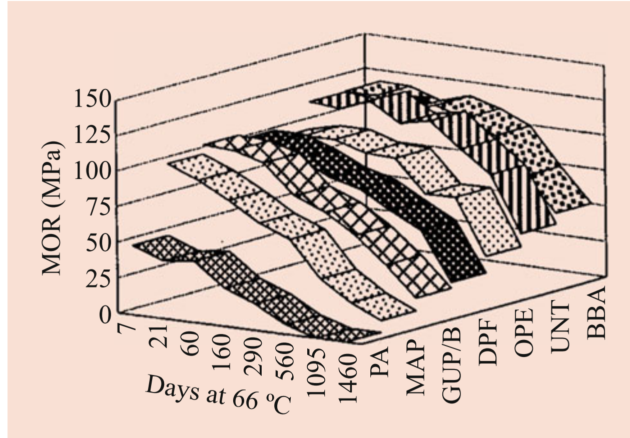


Fig. 17.24 Change in bending strength over steady-state exposure of up to 4 years at 66°C for untreated (UNT) wood and wood treated with phosphoric acid (PA), monoammonium phosphate (MAP), guanylurea phosphate/boric acid (GUP/B), dicyandiamide-phosphoric acid-formaldehyde (DPF), organophosphonate ester (OPE), and borax/boric acid (BBA) [75]

Effects of Adhesives

The fire design of glued wood elements has to take into consideration the type of adhesive used. This is especially true for cross-laminated timber (CLT), which may show falling off of charring layers (bondline failure) at fire exposure. Fire design of CLT is included in Östman et al. [3] and will be included in the next version of Eurocode. An overview is available [71].

There are two possible scenarios for the charring of CLT. With fire-resistant adhesives (i.e., without bondline failure), the charring takes place at the rate β_0 in the same way as for solid timber. With nonfire-resistant adhesives (i.e., with bondline failure), the charring speed of the first 25 mm of each lamella is doubled, i.e., 2β0 (Fig. 17.23).

The fire design of CLT outside Europe is partially different, which creates problems for both producers and users [74].

In North America (both in the US and in Canada) a new system has been developed recently in order to determine if there is a risk for the falling off of charring layers in CLT owing to adhesive failure [73]. The new system consists of testing according to a new qualification standard ANSI/APB PRG 320, which requires that the adhesive used in CLT shall be evaluated for fire performance in a room-scale fire test with unprotected floor-ceiling assembly. This procedure screens out the products that result in premature falling off of charred CLT layers and fire regrowth. A couple of adhesives have shown improved fire performance according to this procedure, and can thus be used in North America.

In Europe the situation is different. No standard procedure is yet available, but there is work in progress [74].

Structural Degradation of FRT Wood Products

It has been observed that FRT wood products, mainly but not exclusively plywood, used as roof sheathing, loses its strength during service conditions. Several incidents have occurred. Extensive studies have been performed, mostly in the US and the main phenomena seem to have been explained. High temperatures in the roof structures have initiated a decaying process in the wood caused by some types of fire retardants. New standards to predict the behavior have been developed. A review of more than 10 years of research has been published [75]. Examples of results are given in Fig. 17.24.

The mechanical strength is important for several applications of FRT wood products in the US, whereas in Europe it seems to be less important, as FRT wood is mainly used for nonstructural purposes. In most cases other properties, e.g., durability against weathering, are considered to be far more essential.

17.3.9 Connections

The main objective of a timber connection is to guarantee the mechanical resistance (R) of load-bearing structures for at least a required time in order to allow safe evacuation of the building and to ensure the safety of fire-fighters. The required time is normally expressed in terms of fire resistance using the ISO standard fire exposure, and is specified by the building regulations of each country. Numerical models for wood connections have been developed in some European countries. The available data concern mainly dowelled and bolted wood-to-wood and wood-to-steel connections [3] (Fig. 17.25).

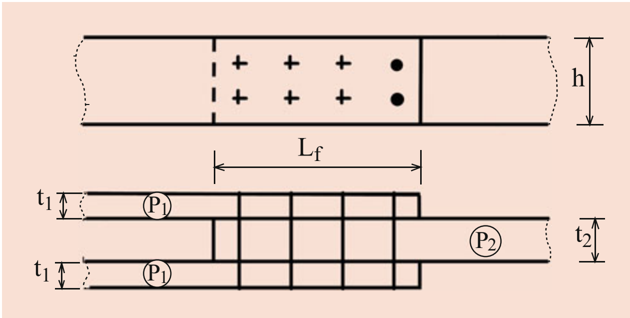


Fig. 17.25 Typical wood-to-wood connection (h is height, t is thickness, L is length, and P is width)

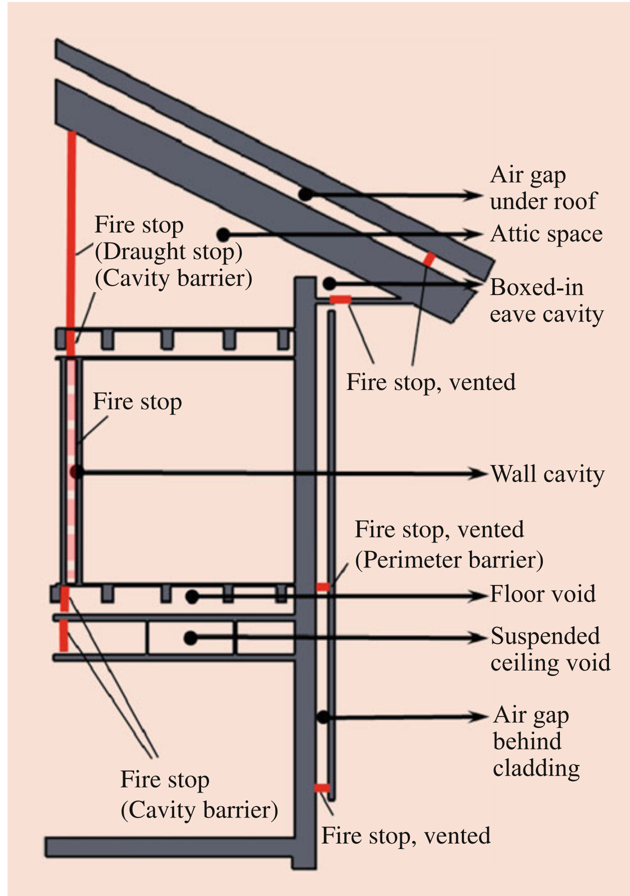


Fig. 17.26 Potential paths of fire and smoke spread within a building that needs fire stops [76]

The Eurocode Design Method

Eurocode [23] gives a method for designing timber connections under standard fire conditions for fire resistance not exceeding R 60. Design rules are given for connections made with nails, bolts, dowels, screws, split-ring connectors, shear-plate connectors, and toothed-plate connectors.

For the connections with wood-side members, the design approaches concern:

- Simplified rules for unprotected and protected connections, and some additional rules for connections with internal steel plates
- A reduced load method for unprotected and protected connections

For connections with external steel plates, the approach concerns the design of protected or unprotected connections.

Other Design Methods Proposed

Other methods combine test results, finite-element approaches and analytical formulae related directly or indirectly to the Eurocode principles. They can be considered as a complement to Eurocode because they cover types of connections or validity domains that can complement the Eurocode approaches. In reality, these studies are still at the research stage. In these methods, the calculation approaches apply to the design of timber-to-timber and steel-to-timber connections with dowel and bolt fasteners. As far as steel-to-timber connections are concerned, the calculation methods apply to connections with one, two, or three slotted-in steel plates.

The next version of Eurocode will include further design methods for wood connections.

17.3.10 Structural Detailing

Wood constructions and elements have a predictable fire performance, but structural details must be carefully designed in order to make the whole building safe from fire [73]. Critical parts are voids, cavities, concealed spaces, penetrations for electricity, ventilation, heating, water, and sewage systems where hidden fires, flames, and smoke might migrate through the building. All these parts are not predictable and must be designed for each building. Such hidden fires can develop rapidly and are hard to find and often discovered too late. They can crawl through the building and break out where least expected and represent a great challenge for the fire services. This is a major problem in older wooden buildings, but can be handled in modern wooden structures by using different kinds of fire stops.

Design recommendations for fire stops are included in guidelines [3, 76, 82].

Basic Principles for Detailing

A schematic illustration of fire spread paths is shown in Fig. 17.26.

Examples of Fire Stops

Fire stops can be massive for enclosed or ventilated cavities and breathable for façades and attics. Massive fire stops (air-tight) are most common, and can consist of wood, rockwool or plaster. Some massive fire stops have been tested and found to meet EI 30 or EI 60.

Structures without cavities, e.g., fully insulated, or massive structures are recommended in the first place.

Some examples of fire stops are given in Figs. 17.27 and 17.28. For ventilated cavities it is essential that the fire stop allows ventilation. Behind façade cladding this can be arranged by using perforated fire stops (Fig. 17.27) [76].

17.3.11 Active Fire Protection of Buildings

Active fire protection increases the time for safe evacuation of a building on fire, i.e., lives are saved. Active fire protection is also the only way of controlling or suppressing a fire in order to minimize fire damage to contents and buildings [3].

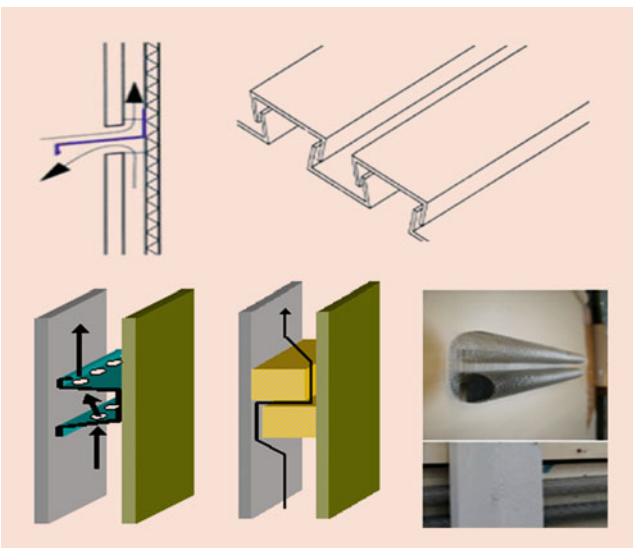


Fig. 17.27 Examples of fire stops in exterior and interior cavities [76]

In contrast to passive fire protection, active fire protection systems become operational only when a fire occurs. They include means of automatic fire detection and devices that control the growth, suppression, or extinguishment of the fire. Large fires are usually due to inbuilt fire precautions being disabled or compromised – for example, doors left open or combustible packaging temporarily being stored in an inappropriate location such as an atrium or stairwell.

Active fire protection measures include provisions of:

- Alarm systems – audible, visual, tactile, etc
- Automatic fire detection – smoke, heat, flame, combustion gas, etc., to trigger alarm systems
- Smoke/heat venting and exhaust control systems
- Automatic fire suppression systems – water, chemical agent, inert gas, etc

Sprinkler Systems

Sprinkler systems were developed by the insurance industry for property protection, and have been in existence for more than a century. Their applicability to the protection of life has been recognized relatively recently, and standards have since been developed to support sprinklers for life safety.

A sprinkler system consists essentially of a reliable water supply feeding an array of individual sprinkler heads (Fig. 17.29) mounted at the correct spacing on an appropriately sized network of hydraulic pipes. Water may be supplied from one or more tanks by gravity or pumps, or taken directly from the tap water system, if this can provide sufficient pressure and flow.

Each sprinkler head is an individual heat detector and a typical operating temperature for a sprinkler head is 68 °C.

Insurers claim that sprinklers have a 99 % success rate in controlling or suppressing fires when they have been correctly specified, installed, and maintained. The design takes into account the size and construction of the building, the category of goods stored in it, and the characterization of

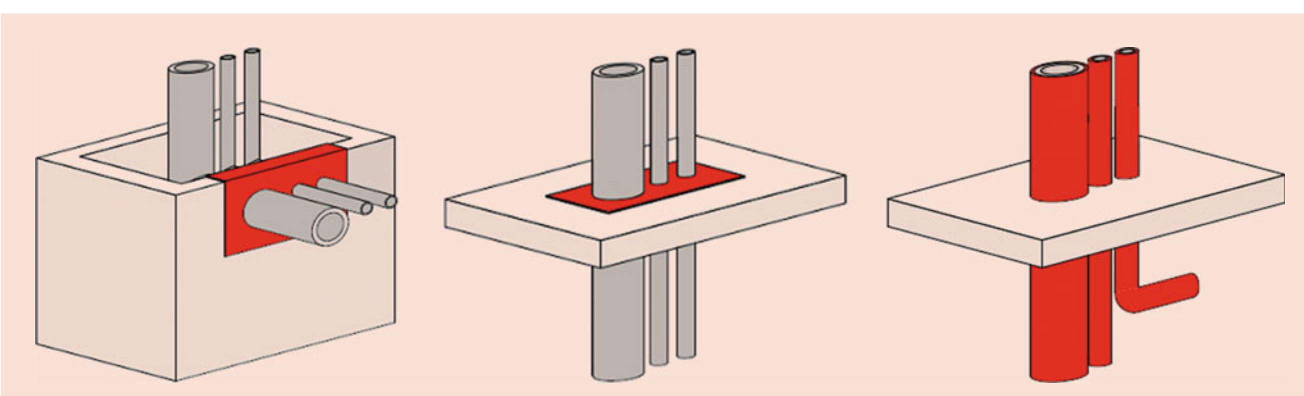


Fig. 17.28 Examples of sealings for building installation systems [3]

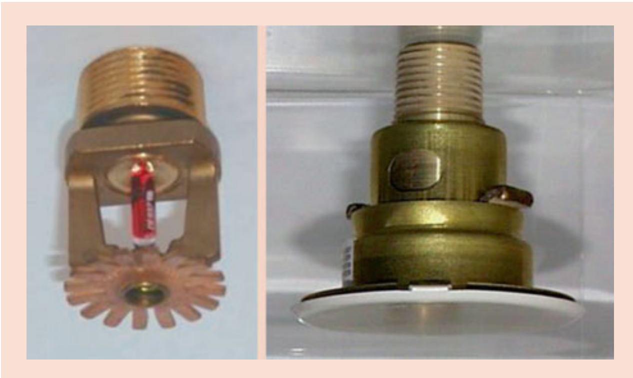


Fig. 17.29 Typical sprinkler heads

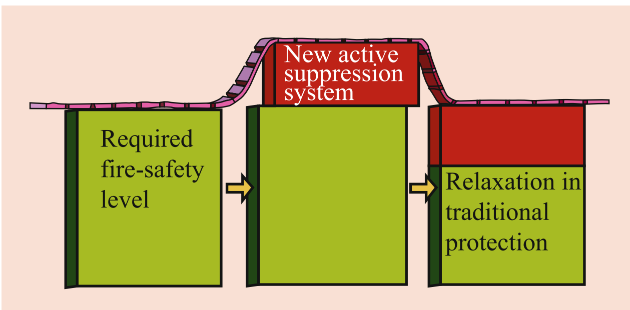


Fig. 17.30 Principle for fire-safety design by sprinklers: Increased fire safety by installation of sprinklers may lead to relaxation in the passive fire protection features and still fulfil the same or higher safety level [76]

occupancy. Water damage from sprinkler systems is minimal. Accidental discharge of water from sprinkler heads is an extremely rare event, as is water leaking from sprinkler pipe work.

Sprinklers are often used in modern buildings, such as airports or storage facilities, to allow extensive open spaces to be created without structural compartment walls. They may also be used to protect premises that are geographically isolated.

Fire Safety Design with Sprinklers

In addition to saving lives, sprinklers may allow for an alternative design of buildings (Fig. 17.30). The requirements of passive fire protection to provide a means of safe egress may be at least partly reduced. This will facilitate a more flexible use of alternative building products. Wooden façades may, for example, be used in sprinkled buildings, which is logical as the risk for flames blowing out of a window from a fully developed fire is eliminated. Wooden linings may be used in sprinkled apartments in multi-story buildings, but not in unsprinkled apartments in some countries [50, 76] (Fig. 17.30).

17.3.12 Performance-Based Design of Buildings

A performance-based approach to fire safety design relies on the use of fire engineering principles, calculations and/or appropriate modeling tools to satisfy building regulations. Instead of prescribing exactly which protective measures are required, it is the required performance of the overall system that is presented against a specified set of design objectives. Fire and evacuation analysis are used together with experimental evidence to assess the effectiveness of the protective measures proposed in the fire safety design of a building [3, 82].

Performance Requirements

The main principle in applying performance-based requirements is that the building should be designed and executed on the basis of design fire scenarios, which must cover the conditions that are likely to occur in the building. The following objectives must be shown to be fulfilled (as in the CPR [51]:

- Load-bearing capacity of structures must not be adversely affected when exposed to fire for a minimum specific period of time
- The generation and spread of fire and smoke must be limited
- Spread of fire to neighboring areas or buildings must be limited
- Occupants must be able to leave the building or be rescued
- The safety of rescue teams must be taken into consideration

This leads to the need for defining criteria to satisfy life safety objectives (safety of occupants and rescue teams) and criteria for loss prevention.

National building regulations may define performance criteria to be applied in structural FSE design, for example:

- A building of more than two stories must not collapse during the fire or cooling phase, *or*
- A building of not more than two stories must not collapse during the period of time required to secure evacuation, rescue operations, and to control the fire

There are basically two ways to attest that a design solution fulfils the performance criteria:

1. Based on absolute values:
   - Determination of the risk for nonperformance of the solution
   - Comparison of this risk with a limiting risk value agreed to represent a tolerable risk
2. Based on relative values:
   - Assessment of the risks related to the FSE design solution

- Assessment of the risks that would result from application of the prescriptive rules of fire regulations (deemed-to-satisfy solution [DTS])
- Comparison of these risks

Verification Through a Tolerable Risk Level

The risks involved in a potential structural failure vary widely, depending on the damage that might be caused. For example, the collapse of a basically unmanned single-story warehouse is completely different than the collapse of a multi-story building having a large number of occupants. Fire safety design is aimed at providing solutions with risk levels that our society can tolerate. As the risk is composed of the probability p_f of the failure – or more generally, the unwanted event – and the associated consequence C, high-consequence events must have considerably lower probability of occurrence than low-consequence events. However, it is important to realize and acknowledge the fact that there is always some – though very small – probability that the unwanted and unexpected event will happen. Consequently, a tolerable risk level greater than zero exists.

Risk-Based Verification

There are numerous methods for risk assessments in fire. A fairly easy way is to use index methods. Fire risk indexing is a link between fire science and fire safety.

An index method for the assessment of fire risks in multi-story apartment buildings Fire Risk Index Method: Multi-story Apartment Buildings (FRIM-MAB) has been developed [77, 78]. It is based on a hierarchy structure for the fire safety in a building (Fig. 17.31). The highest level is the *policy*, then the *objectives*, at the next level the *strategies*, and finally several *parameters*. The parameters are subdivided into quantitative *sub-parameters*, organized into *decision tables*, and given a *grade*. When the structure is fixed, the objectives, strategies, and parameters are given *weights*.

The grades and weights are multiplied giving a relative value for each parameter. The sum of these weighted grades results in a single index value for the whole building that can be used to compare with index values for other buildings or different fire safety measures. Basic requirements in building law must of course be fulfilled.

The index method FRIM-MAB gives an overview of the fire safety in the building. It includes active and passive fire design, safe evacuation, and maintenance. Its repeatability is good. It can be used to rank the fire safety in different buildings, especially multi-story apartment buildings (Table 17.17).

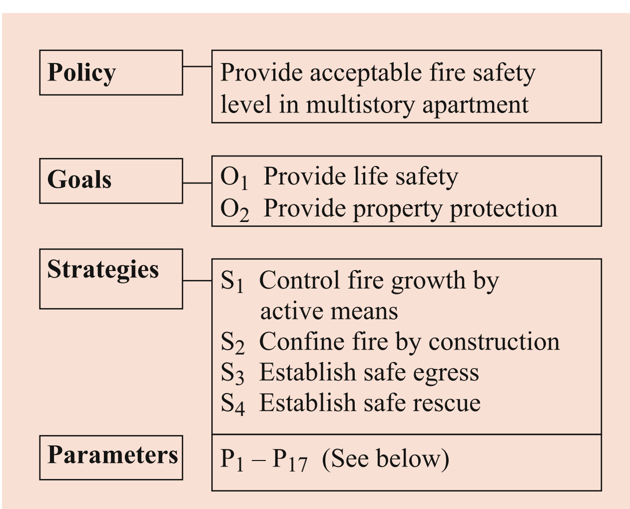


Fig. 17.31 Structure and levels of the index method Fire Risk Index Method: Multi-story Apartment Buildings (FRIM-MAB [77])

Table 17.17 Parameters for the Fire Risk Index Method: Multi-story Apartment Buildings (FRIM-MAB) method

Parameters		Definition
P1	Linings in apartment	Possibility of internal linings in an apartment to delay the ignition of the structure and to reduce fire growth
P2	Suppression system	Equipment and systems for suppression of fires
P3	Fire service	Possibility of fire services to save lives and to prevent further fire spread
P4	Compartmentation	Extent to which the building space is divided into fire compartments
P5	Structure – separating	Fire resistance of building assemblies separating fire compartments
P6	Doors	Fire and smoke separating function of doors between fire compartments
P7	Windows	Windows and protection of windows, i.e., factors affecting the possibility of fire spread through the openings
P8	Façades	Façade material and factors affecting the possibility of fire spread along the façade
P9	Attic	Prevention of fire spread to and in the attic
P10	Adjacent buildings	Minimum separation distance from other buildings
P11	Smoke control system	Equipment and systems for limiting spread of toxic fire products
P12	Detection system	Equipment and systems for detecting fires
P13	Signal system	Equipment and systems for transmitting a fire alarm
P14	Escape routes	Adequacy and reliability of escape routes
P15	Structure – load-bearing	Structural stability of the building when exposed to a fire
P16	Maintenance and information	Inspection and maintenance of fire safety equipment, escape routes, etc., and information to occupants on suppression and evacuation
P17	Ventilation system	Extent to which the spread of smoke through the ventilation system is prevented

Verification Through a Deemed-to-Satisfy Solution
Verification of safety through comparison with a deemed-to-satisfy solution (DTS) solution is a straightforward method that has the great advantage that the designer is not required to justify the safety of the solution. The drawback is that it requires two analyses: one for the FSE design, and one for the design that complies with the classes and numerical requirements given in the fire regulations [3].

In brief, using fire safety assessment of structures as an example, the process is as follows:

1. Establish the design fires using the fire-load entities
2. Carry out the FSE analysis of the design have accepted, including the assessment of structural adequacy
3. Assess the likelihood of structural failure in the FSE design
4. Carry out the FSE analysis, including assessment of structural adequacy for a similar building (or part of it) with design solutions taken from the fire regulations (the DTS design solution)
5. Assess the likelihood of structural failure in the DTS design, using the same failure criterion as used for the FSE solution
6. Compare the results and, if the FSE solution gives at least as low a failure likelihood as the DTS solution, the FSE solution is acceptable

17.3.13 Quality Control of Workmanship

Wood frame construction consists of a combination of several different materials, which are designed and installed to fulfil multiple performance functions such as fire safety and acoustic performance. The methods used for assembling/erecting these multiple layers are vital to ensuring adequate performance. Building practices vary. In some countries, the majority of installation is undertaken in the factory, sometimes including windows, doors, service installations, and even whole three-dimensional compartment volume elements, and only final assembly is undertaken on site. In other countries, only the frames are manufactured off site, with the majority of lining and installation work undertaken on site [3].

Although the assembly sequences may differ, the requirements for ensuring adequate performance levels are identical. As an example, insulation, for example, mineral wool must be mounted carefully and must be in direct contact with wooden beams and girders to ensure adequate fire performance. Empty voids can lead to premature exposure of wooden elements in the event of a fire, and can lead to earlier charring and therefore decreased fire resistance. Careful installation of insulating products is particularly important in nominally empty attic areas, where the insulation tends to be less carefully installed owing to the non-occupied state of the roof space.

Fixings for securing claddings are essential for fire resistance. If they are too short, the cladding will be prone to premature falling off, and wooden beams and girders will be exposed to fire at an earlier stage. This will lead to earlier charring and can reduce the fire resistance.

The appropriate installation of fire stops and sealings for building installation systems are essential to ensure the fire performance of a wooden structure. They can be checked only during the construction period, and the quality of workmanship of such details should be monitored closely by the responsible contractor or fire-safety personnel.

Self-monitoring by the contractor or fire-safety personnel is an important process, and should be mandated and formalized whenever possible. The responsibilities of interacting trades must be clearly stated, and overarching project management processes communicated and enforced at the beginning of a building project.

Fire protection documentation should always be produced; normally by the fire safety personnel. This is mandatory in some countries.

Inspection plans and checklists should also be produced for both design and execution, and be communicated to all parties. They should specify in detail the inspection areas and responsibilities. Critical areas, such as interfaces between the various control functions, need special attention.

Rules for inspection and control have been published in a recent Nordic standard INSTA 952 [79]. It includes rules for controlling fire safety design throughout the design period.

17.3.14 Fire Safety During Construction

Fires during building construction and refurbishment are quite common. The reasons for a fire occurring range from arson to accident; some are related to the work processes on site. The overall number of fires during construction and associated losses is not easily approximated, as detailed statistics are not available. Available fire statistics do not differentiate between the types of construction involved. Only limited information is available on the risk of a fire occurring on a construction site, but it is evident that a fire risk is present for all forms of construction, largely independently of materials used and of the size of the construction site. The occurrence of fires during construction, its spread and the consequent risk to life, property, and business, are recognized and have prompted some main codes of practice, e.g. Fire Prevention on Construction Sites [80].

Essential parts of fire safety on building sites are to install fire separating elements/walls as early as possible in the building process to avoid risks for fire spread, and to consider using temporary or permanent sprinklers [81].

17.4 Conclusions

Wood is a heterogeneous material and its thermal degradation on fire exposure is complicated and dependent on many factors. But the fire performance of wood products in building fires is predictable and wooden structures can reach high fire resistance ratings. However, there are a number of aspects that need to be considered for the fire-safe use of wood in buildings:

- The highest reaction to fire performance classes cannot be reached by wood products. Wood products usually reach the European reaction to fire class D and the North American flame spread class C
- Higher fire performance with regard to reaction to fire can be achieved by fire-retardant treatments, but their long-term performance has to be verified, especially in exterior applications
- Untreated wood products may be more widely used as visible surfaces, if the buildings are sprinkled, as sprinklers control and extinguish the fire in its initial stage and flashover will not reached
- In addition, sprinkler installations save lives, in all types of buildings
- Detailing in wooden structures is important to avoid fire spread through cavities, penetrations, and connections
- Quality control of workmanship on building sites is essential to verify that the intended fire safety design is implemented in practice

More information on Fire Safe Use of Wood in Buildings is available [82].

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