CHAPTER 11

Analytical Methods for Determining Fire Resistance of Timber Members

Robert H. White

Introduction

The fire resistance ratings of wood members and assemblies, as of other materials, have traditionally been obtained by testing the assembly in a furnace in accordance with American Society for Testing and Materials (ASTM) Standard E119.[1] These ratings are also published in listings, such as the Underwriters Laboratories *Fire Resistance Directory*[2] or the Gypsum Association's *Fire Resistance Design Manual*,[3] and in publications of the model building code organizations. The ratings listed are limited to the actual assembly tested and normally do not permit modifications such as adding insulation, changing member size, changing or adding interior finish, or increasing the spacing between members. Code interpretation of the test results sometimes allows the substitution of larger members, thicker or deeper assemblies, smaller member spacing, and thicker protection layers, without reducing the listed rating. A new ASTM standard4 provides guidelines on such extension of fire endurance results obtained from the standard ASTM E119 fire test. A fire-endurance design procedure for wood beam and columns and a procedure for wood-frame walls have U.S. and Canadian building code acceptance. In Europe, the new Eurocode 5[5] provides calculation methods at three levels of complexity. In addition, other procedures and models have been proposed or are being developed.

When attention is given to all details, the fire endurance of a wood member or assembly depends on three items:

1. Performance of its protective membrane (if any)
2. Extent of charring of the structural wood element
3. Load-carrying capacity of the remaining uncharred portions of the structural wood elements

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The following sections review the methods available for determining the contribution of each item and discuss the major properties of wood that affect the thermal and structural response of wood assemblies or components.

Contribution of the Protective Membrane

Gypsum wallboard and plywood paneling are two common types of protective membrane, which is the first line of resistance to a fire in wood construction. In a protected assembly, the fire resistance rating is largely determined by the type and thickness of the protective membrane. The effects of the protective membrane on the thermal performance of an assembly are included in Harmathy's ten rules of fire endurance rating.[6] These ten rules (Figure 4-11.1) provide guidelines to evaluate the relative effects of changes in materials on the fire resistance rating of an assembly. However, there are exceptions to some of these general rules. The rules apply primarily to the thermal performance of the assembly.

The contribution of the protective membrane to the fire resistance rating of a light-frame assembly, is clearly illustrated in the component additive calculation procedure discussed in the following subsection. Brief discussions of direct protection of wood members and numerical heat transfer models are also presented.

Component Additive Method

The Component Additive Method (CAM) is a calculation procedure to determine the fire resistance ratings of light-frame wood floor, roof, and wall assemblies. With this procedure, as with Harmathy's rules 1 and 2, one assumes that times can be assigned to the types and thicknesses of protective membranes and that an assembly with two or more protective membranes has a fire resistance rating at least that of the sum of the times assigned

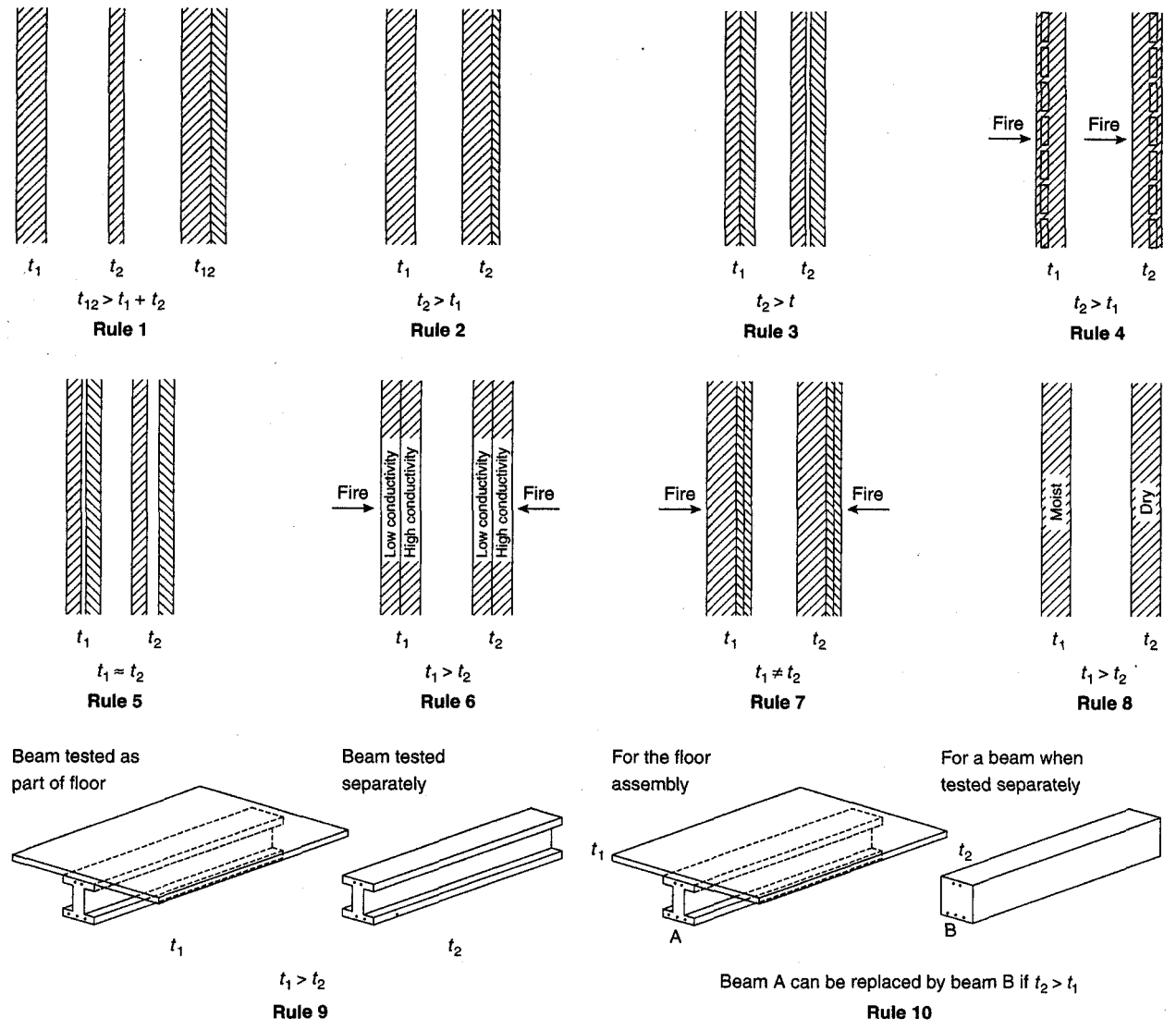

Figure 4-11.1. ***Harmathy's ten rules of fire endurance.***[6]

for the individual layers and the times assigned to the framing. CAM was developed by the National Research Council of Canada (NRCC), and has gained code approval in both the United States and Canada.

The times assigned to the protective membranes (Table 4-11.1), the framing (Table 4-11.2), and other factors are added together to obtain the fire resistance rating for the assembly. The times are based on empirical correlation with actual ASTM E119 tests of assemblies. The ratings obtained in these tests ranged from 20 to 90 min. The times given in Table 4-11.1 are based on the membrane's ability to remain in place during fire tests. The type of fasteners and their spacing on the protective membrane can be critical factors in the performance of the membrane in a fire endurance test. Reference should be made to similar tested assemblies. The addition of insulation to a wall assembly can increase its fire resistance. Adding rock wool

Table 4-11.1 ***Time Assigned to Protective Membranes***[a]

Description of Finish	Time (min)
9.5-mm ($^3/_8$-in.) Douglas fir plywood, phenolic bonded	5
13-mm ($^1/_2$-in.) Douglas fir plywood, phenolic bonded	10
16-mm ($^5/_8$-in.) Douglas fir plywood, phenolic bonded	15
9.5-mm ($^3/_8$-in.) gypsum board	10
13-mm ($^1/_2$-in.) gypsum board	15
16-mm ($^5/_8$-in.) gypsum board	20
13-mm ($^1/_2$-in.) type X gypsum board	25
16-mm ($^5/_8$-in.) type X gypsum board	40
Double 9.5-mm ($^3/_8$-in.) gypsum board	25
13-mm + 9.5-mm ($^1/_2$-in. + $^3/_8$-in.) gypsum board	35
Double 13-mm ($^1/_2$-in.) gypsum board	40

[a]The applicable building code should be checked for acceptance of, modification to, and limitations on the procedure. There are specific requirements for the installation of some of the membranes.

Table 4-11.2 ***Time Assigned for Contribution of Wood Frame***[a]

Description of Frame	Time (min)
Wood wall studs, 406 mm (16 in.) on center	20
Wood floor and roof joists, 406 mm (16 in.) on center	10

[a]Minimum size for studs is nominal 51 mm by 102 mm (2 in. by 4 in.). Wood joists must not be less than nominal 51 mm (2 in.) in thickness. The spacing between studs or joists cannot exceed 406 mm (16 in.) on center. The applicable building code should be checked for acceptance of, modification to, and limitations on the procedure.

or slag mineral wood insulation batts for additional protection to the wood stud wall generally has an assigned time of 15 minutes, which is added to the times for the framing and for the protective membrane to obtain the rating for the wall assembly. Assigned times, if any, for glass fiber insulation depend on the codes. Adding insulation to a floor or roof assembly can decrease its fire resistance, depending on its location within the assembly and the method of attachment.

For asymmetrical wall assemblies, the rating is based on the side with the lesser fire resistance. For exterior walls rated only from the interior and floor/roof assemblies, there are minimal requirements for the membrane on the side or top of the assembly not exposed to the fire, in order to ensure that the wall or floor/roof assembly does not fail because of fire penetration or heat transfer through the assembly. Specific alternative membranes are identified for the face of wood stud walls not exposed to fire (exterior) and for the flooring or roofing over wood joist framing.

The membrane on the side not exposed to fire (the outside or top) may also be any membrane listed in Table 4-11.1 with an assigned time of 15 min or greater.

The application of the method in the building codes is generally limited to 60 or 90 min. Additional information can be found in publications of the American Forest & Paper Association7 and the Canadian Wood Council? The applicable building code should be checked for acceptance of, modifications to, and limitations on the procedure. There are differences between the codes in what is accepted.

CAM gives flexibility, for example, in calculations for plywood and gypsum board combined as an interior finish.

EXAMPLE 1:

The calculated fire resistance rating of a wood stud exterior wall (nominal 2-in. × 4-in. [51-mm × 102-mm] studs, 16 in. [406 mm] on center) with 5/8-in. (16-mm) Douglas fir phenolic-bonded plywood over 1/2-in. (13-mm) type X gypsum wallboard on the side exposed to fire is

From Table 4-11.1:	
16-mm (5/8-in.) Douglas fir plywood, phenolic bonded	15 min
13-mm (1/2-in.) type X gypsum board	25 min
From Table 4-11.2:	
Wood stud framing	20 min
Calculated rating (total)	60 min

Mineral wool insulation could be used to increase the fire rating to 75 minutes.

Other Methodologies

The times assigned to the protective membranes in the component additive method are not the "finish ratings" of the material cited in test reports or listings. A finish rating of a protective membrane is generally defined as the time to reach either an average temperature rise of 139°C (250°F) or a maximum rise of 181°C (325°F), as measured on the plane of the wood framing member nearest the fire. Since the charring of wood is associated with a temperature of 300°C (550°F), another method is to assume that the membrane will protect any wood framing for at least the time of the finish rating of the membrane in a test involving wood framing. The fire rating of the entire assembly with the substituted member is assumed to be at least equal to the finish rating of the protective membrane in the test with the solid sawn wood framing. This approach is described as the onset of char method in New Zealand publications.[9]

In a Swedish additive method,[10] the fire separation of nonloaded wall assemblies is calculated as the sum of the contribution to fire resistance from each layer of material:

$$b_{tot} = b_1k_1 + b_2k_2 + \; b_2k_2 + \cdots = \; b_nk_n \qquad (1)$$

where

b_{tot} = total fire resistance of the wall

b_n = basic fire resistance of layer n

k_n = coefficient of position indicating where the layer is located in relation to the fire

Direct Protection of Wood Members

The steel industry improves the fire endurance of steel members by directly covering them with fire-resistive panels or coatings. Currently, the marketing of fire-resistive coatings for use on wood is very limited or nonexistent. The fire-retardant coatings marketed for wood are only designed and recognized for use to reduce the spread of flames over a surface (flamespread).

Depending upon its thickness and durability under fire exposure, a coating may merely delay ignition of the wood for a few minutes or may provide an effective insulative layer that reduces the rate of charring. For both fire-retardant coatings and fire-resistive coatings, their performance as a fire-resistant membrane on wood has been evaluated.[11-13] In some full-scale testing of beams, those coated with an intumescent fire retardant produced improvements less than that obtained in earlier tests in a small-scale furnace.[14] Bending of the beams during the fire test resulted in adhesion problems. Tests on coated timber members were also reported in Finland and U.S.S.R.[15] There is limited published data on the protection provided by directly covering a wood member with gypsum board or other nonwood panel products. As previously noted, finish ratings listed for panel products used in ASTM E119 tests of assemblies have been used to estimate the delay in the onset of char formation

provided by the panel product. Gardner and Syme[16] found that gypsum board not only delayed the onset of char formation but also reduced the subsequent rate of char formation. In their 2-hour tests, 13-mm- (1/2-in.-) thick gypsum board on wood beams reduced the depth of char by approximately 40 percent. Of the 40 percent, only 17 percent was credited to the initial delay in char formation.

Numerical Heat Transfer Models

The protective membrane contributes to fire resistance by providing thermal protection. Numerical heat transfer methodologies are available to evaluate this thermal protection. Fung[17] developed a one-dimensional finite difference model and computer program for thermal analysis of construction walls. Gammon[18] developed a two-dimensional finite element heat transfer model for wood stud wall assemblies. WALL2D, developed by Forintek Canada,[19,20] is a two-dimensional finite-difference model for predicting heat transfer through wood-stud walls exposed to fire. Difficulties in modeling the charring of wood and the physical deterioration of the panel products complicate these numerical methodologies. Recent research on such models includes activities in Canada,[20] Sweden,[21] New Zealand,[22,23] and Australia.[24] An important application of such models is the determination of the fire endurance of an assembly when the time-temperature curve is a natural or parametric fire exposure. This application is important for performance-based building codes.

Numerical heat transfer models are used not only to model the performance of the protective membranes but also to model the charring of the structural wood members, the second major factor in the fire endurance of a wood member or assembly.

Charring of Wood

Wood undergoes thermal degradation (pyrolysis) when exposed to fire. (See Figure 4-11.2.) The pyrolysis and combustion of wood have been studied extensively. Literature reviews include publications by Browne,[25] Schaffer,[26,27] Hall et a1.,[28] and Hadvig.[29] By converting the wood to char and gas, pyrolysis results in a reduction in the wood's density. The pyrolysis gas undergoes flaming combustion as it leaves the charred wood surface. Glowing combustion and mechanical disintegration of the char eventually erode or ablate the outer char layer.

The charring rate generally refers to the linear rate at which wood is converted to char. Under standard fire exposure, the charring rates tend to be fairly constant after a higher initial charring rate.

Establishing the charring rate is critical to evaluating fire resistance, because char has virtually no load-bearing capacity. There is a distinct demarcation between char and uncharred wood. The base of the char layers is wood reaching a temperature of approximately 300°C (550°F). SI conversion of inch-pound units has resulted in 288°C, 290°C, and 300°C being used for 550°F. To determine the charring rate, we use both empirical models based on experimental data and theoretical models based on chemical and physical principles.

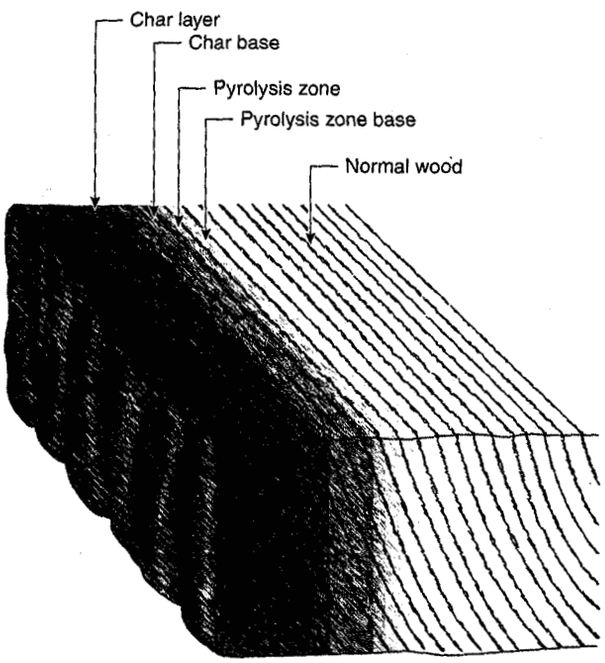

Figure 4-1 1.2. Degradation zones in a wood section.

Standard ASTM E119 Fire Exposure

Expressions for charring rate in the standard ASTM E119 test are the result of many experimental studies. The empirical model that is most generally used assumes a constant transverse-to-grain char rate of 0.6 mm/min. ($1^1/_2$ in./hr) for all woods, when subjected to the standard fire exposure. There are differences among species associated with their density, chemical composition, and permeability. In addition, the moisture content of the wood affects the charring rate. The charring rate parallel to the grain of wood is approximately twice that transverse to the grain.[28] As a beam or column chars, the comers become rounded. The rounding is generally considered to have a radius equivalent to the char depth on the sides.

Schaffer[30] reported transverse-to-grain charring rates as a function of density and moisture content for Douglas fir, southern pine, and white oak. The regression equations for B (min per mm., the reciprocal of charring rate) were

$$B = (0.002269 + 0.00457u)\,r + 0.331 \text{ for Douglas fir} \quad (2)$$

$$B = (0.000461 + 0.00095u)\,r + 1.016 \text{ for southern pine} \quad (3)$$

$$B = (0.001583 + 0.00318u)\,r + 0.594 \text{ for white oak} \quad (4)$$

where

u = moisture content (fraction of oven-dry mass)

r = density (dry mass, volume at moisture content u)

White[31] developed an empirical model based on eight species. The char rate equation was of the form

$$t = m x_c^{1.23} \tag{5}$$

where

t = time (min)

m = char rate coefficient

x_c = char depth (mm)

The char rate coefficients ranged from 0.48 to 0.72 min/mm$^{1.23}$ for the eight species.[31,32] The char rate coefficient could be estimated with the equation

$$m = -0.147 + 0.000564\rho + 1.21u + 0.532f_c \tag{6}$$

where

ρ = oven-dry density (kg/m^3)

u = moisture content (fraction of oven-dry mass)

f_c = char contraction factor (dimensionless)

The char contraction factor was the thickness of the char layer at the end of the fire exposure divided by the original thickness of the wood layer that was charred (char depth). Average values for the char contraction factor were 0.60 for southern pine, 0.83 for western red cedar, 0.86 for redwood, 0.82 for Engelmann spruce, 0.52 for basswood, 0.59 for hard maple, 0.70 for red oak, and 0.67 for yellow poplar. Recent char rate experiments have been reported in Australia,[16] Europe,[33] and New Zealand.[34]

In Eurocode 5,[5] the linear charring rates listed are 0.64 mm/min for glued laminated softwood timber with a characteristic density of 290 kg/m^3, 0.67 for solid softwood timber with a characteristic density of 290 kg/m^3, and 0.54 mm/min for solid or glued laminated hardwood with a characteristic density of 350 kg/m^3. The design values for charring rate depend on the fire endurance methodology being used. The effect of the rounding of the charred member can be taken into account by increasing the values for char rate as is done in Eurocode 5. Eurocode 5 design values for linear charring rate include 0.7 mm/min for glued laminated softwood timber with a characteristic density of 290 kg/m^3, 0.8 for solid softwood timber with a characteristic density of 290 kg/m^3; 0.5 mm/min for solid or glued laminated hardwood with a characteristic density of 450 kg/m^3 and 0.7 mm/min for characteristic density of 290 kg/m^3. Additional design values can be found in the Eurocode 5. Some of the charring rate values for density ρ_o are adjusted for other characteristic densities, ρ_k, with a coefficient, k_ρ, equal to $\sqrt{\rho_o/\rho_k}$ as a multiplier.[5]

Assumption of a constant charring rate is reasonable when the member or panel product is thick enough to be treated as a semi-infinite slab. For smaller dimensions, the charring rate increases once the temperature has risen above the initial temperature at the center of the member or at the unexposed surface of the panel.

Kanury and Holve[35] suggest the model

$$\frac{\ell}{t} \approx \left(\frac{2}{a}\right)\left(1 - \frac{b\ell}{a}\right) \tag{7}$$

where

ℓ = thickness of slab (mm)

t = fire endurance time (min)

a,b = constants

They consider the 2/a factor an ideal charring rate and the ratio $b\ell/a$ as a correction factor accounting for thickness and thermal diffusion effects.

Noren and Ostman[36] provided the equation

$$b_m = 1.128t + 0.0088t^2 \tag{8}$$

where

b_m = contribution to fire resistance (min)

t = panel thickness (mm)

The equation is based on data for various wood-based panel products. Differences in the fire resistance at equal thickness depended on panel density, moisture content, type of adhesive, and the structural composition of the panel. The effect of fire-retardant treatment and adhesives on fire resistance depends on the type of adhesive or treatment. Lumber bonded with phenolic or resorcinol adhesives has a charring rate consistent with that of solid wood. Fire-retardant treatments are designed to reduce flamespread. The fire retardant's effect on the charring rate may be to only slightly increase the time until ignition of the wood. Some fire retardants reduce flammability by lowering the temperature at which charring occurs. This may increase the charring rate. However, a few fire retardants have been found to improve charring resistance.[37]

Nonstandard Fire Exposures

The above equations were stated to apply to the standard ASTM E119 fire exposure.[1] Data on charring rates for other fire exposures have been limited. Schaffer[22] provided data for constant temperatures of 538°C (1000°F), 815°C (1500°F), and 927°C (1700°F). Lau and White[38] presented data for constant 500°C and an empirical model for constant or variable temperatures. The charring rate is a function of the external flux. For a range of 20 to 3300 kW/m^2, Butler[39] calculated the char rate (mm/min) to be 0.022 times the irradiance (kW/m^2). Because of increased testing with heat release rate calorimeters, char rate data as a function of external heat flux are becoming more available.[40–45] In tests of spruce, charring rates obtained were 0.56, 0.80, and 1.02 mm/min. for external heat fluxes of 25, 50, and 75 kW/m^2, respectively[42] In tests of southern pine, the linear charring rate ranged from 0.44 mm/min at 18 kW/m^2 to 0.85 mm/min at 55 kW/m^2.[40,41] Charring rate has been found to be proportional to the ratio of external heat flux over density.[42,44]

Hadvig's Equations for Nonstandard Fire Exposure

Hadvig[29] has developed equations for nonstandard fire exposure. The charring rate in a real fire depends

upon the severity of the fire to which the wood is exposed. The fire severity depends upon such factors as the available combustible material (fire load) and the available air supply (design opening factor).

The design fire load is

$$q = k \cdot \frac{Q}{A_t} \tag{9}$$

where

q = design fire load (MJ/m²)

k = transfer coefficient (dimensionless)

Q = sum of the products of mass and lower calorific value of materials to be found in the compartment (MJ)

A_t = total internal area of the compartment, including floor, walls, ceiling, windows, and doors (m²)

The transfer coefficients are given in Table 4-11.3 for different types of compartments and geometrical opening factors. In the case of fire compartments whose bounding structures do not come under any of the types A-H, k is usually determined by a linear interpolation in the table between appropriately chosen types of compartments.

The geometrical opening factor is

$$F' = \frac{A\sqrt{h}}{A_t} \tag{10}$$

where

Table 4-1 1.3 ***The Transfer Coefficient, k[29,46]***

Type of Fire Compartments	Geometrical Opening Factor, F'					
	0.02	0.04	0.06	0.08	0.10	0.12
A	1.0	1.0	1.0	1.0	1.0	1.0
B	0.85	0.85	0.85	0.85	0.85	0.85
C	3.0	3.0	3.0	3.0	3.0	2.5
D	1.35	1.35	1.35	1.50	1.55	1.65
E	1.65	1.50	1.35	1.50	1.75	2.00
F[b]	1.0–0.5	1.0–0.5	0.8–0.5	0.7–0.5	0.7–0.5	0.7–0.5
G	1.50	1.45	1.35	1.25	1.15	1.05
H	3.0	3.0	3.0	3.0	3.0	2.5

[a]A = (Standard fire compartment) The average consisting of brick, concrete, and gas concrete.

B = Concrete, including concrete on the ground

C = Gas concrete (density 500 kg/m³)

D = 50 percent concrete, 50 percent gas concrete (density 500 kg/m³)

E = 50 percent gas concrete (density 500 kg/m³), 33 percent concrete, and 17 percent laminate consisting of (taken from the inside) 13-mm plasterboard (density 500 kg/m³), 10-cm mineral wool (density 50 kg/m³), and brick (density 1800 kg/m³)

F = 80 percent steel plate, 20 percent concrete. The fire compartment is comparable to a storehouse or other building of a similar kind with an uninsulated roof, walls of steel plate, and floor of concrete.

G = 20 percent concrete and 80 percent laminate consisting of a double plasterboard (2 x 13 mm) (density 790 kg/m³), 10-cm air space, and another double plasterboard (2 x 13 mm) (density 790 kg/m³)

H = Steel plate on either side of 100-mm mineral wool (density 50 kg/m³)

[b]The higher values apply to q < 60 MJ/m²; the lower values apply to q > 500 MJ/m². Intervening values are found by interpolation.

F' = geometrical opening factor (m^1/2)

A = total area of windows, doors, and other openings in walls (i.e., vertical openings only) (m²)

h = weighted mean value of the height of vertical openings, weighted against the area of the individual openings (m)

The design opening factor is

$$F = F' \cdot k \cdot f \tag{11}$$

where

F = design opening factor (m^1/2)

F' = geometrical opening factor (m^1/2)

k = transfer coefficient of bounding structure (dimensionless)

f = coefficient (dimensionless) to account for horizontal openings

The dimensionless coefficient, f, (Figures 4-11.3 and 4-11.4) increases the opening factors when there are horizontal openings. For only vertical openings, f is equal to 1.

Hadvig's[29] equations are

$$\theta = 0.0175 \frac{q}{F} \tag{12}$$

$$\beta_0 = 1.25 - \frac{0.035}{F + 0.021} \quad \text{for} \quad 0.02 \le F \le 0.30 \tag{13}$$

$$X = \beta_0 \cdot \tau \quad \text{for} \quad 0 \le \tau \le \frac{\theta}{3} \tag{14}$$

$$X = \beta_0\left(-\frac{1}{12}\theta + \frac{3}{2}\tau - \frac{3}{4}\frac{\tau^2}{\theta}\right) \quad \text{for} \quad \frac{\theta}{3} \le \tau \le \theta \tag{15}$$

where

q = time at which maximum charring is reached for the values used for F and q (min)

b_0 = initial value of rate of charring (mm/min)

X = charring depth (mm)

F = design opening factor (m^1/2) (defined in Equation 11)

q = design fire load (MJ/m²) (defined in Equation 9)

t = time (min)

These equations are valid for fire exposures less than 120 min. and for a room where the combustible material is wood. Plastic burns more intensely and for a shorter time than wood. When the combustible materials in the room are plastics, Equations 12 and 13 are therefore modified for faster char rate (b_0 is 50 percent higher), shorter time is allowed for maximum charring (q is cut in half), and Equation 14 is applicable for t < q.[29]

Equations 12 through 15 are for glued timber with a density of 470 kg/m³ including a moisture content of 10 percent and minimum width of 80 mm or greater or square members of minimum 50 X 50 mm. Equations 14 and 15 are valid only for $0 < X < b/4$, where b is the dimension of the narrow face of a rectangular member. For

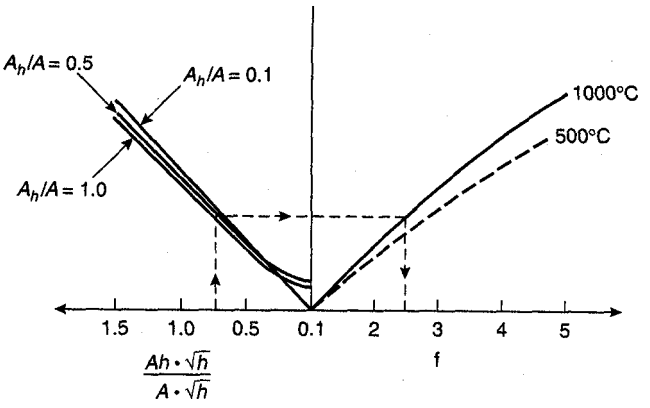

Figure 4-11.3. ***Diagram for the determination of f for fire temperatures of 500°C and 7000°C.***

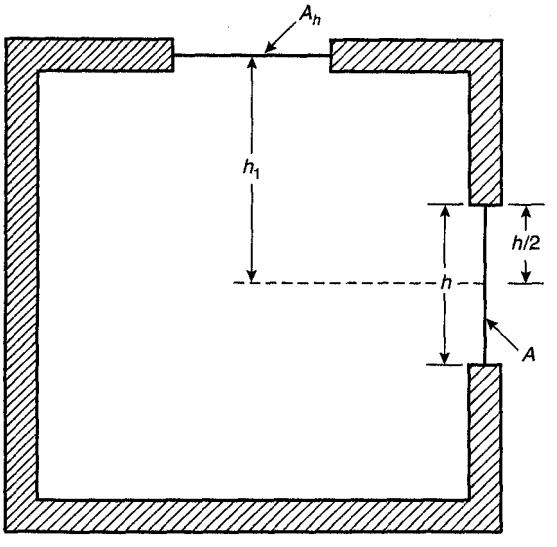

Figure 4-11.4. ***Simplified sketch of vertical cross section of ventilated compartment with notation.***[20]

dimensions of nonsquare cross sections between 30 and 80 mm, the ratio of the original dimensions must be equal to or greater than 1.7, the charring depth perpendicular to the wide face is *X*, and the charring depth perpendicular to the narrow face is determined by multiplying Equation 14 or 15 by the dimensionless quantity

$$1.35 - 0.0044(b) \qquad (16)$$

where b equals the dimension of the narrow face (mm).

EXAMPLE 2:

The room is a standard fire compartment consisting of brick, concrete, and gas concrete. The floor area is 5 X 10 m, and the height is 3 m. The openings are one window 1.5 m high and 2 m wide, three windows 1.5 m high and 1 m wide, and one skylight 1.5 m × 3 m. The skylight is 2 m above the midheight of the windows. The fire load is 6 m³ of wood.

Assuming a fire temperature of 1000°C, a wood density of 500 kg/m³, and lower calorific value of 17 MJ/kg, describe the charring of a 38- × 250-mm wood beam exposed on three sides after 8 min of the fire.

The geometrical opening factor (Equation 10) is

$$F' = \frac{A\sqrt{h}}{A_t} = \frac{[1(1.5 \times 2) + 3(1.5 \times 1)]\sqrt{1.5}}{[2(5 \times 10) + 2(3 \times 5) + 2(3 \times 10)]}$$

$$= \frac{7.5\sqrt{1.5}}{190} = 0.048 \text{ m}^{1/2}$$

The design opening factor (Equation 11) is

$$F = F' \cdot k \cdot f$$

The k is obtained from Table 4-11.3 (k = 1.0 for type A, F' = 0.048). The f is obtained from Figures 4-11.3 and 4-11.4.

$$\frac{A_h\sqrt{h_1}}{A\sqrt{h}} = \frac{(1.5 \times 3)\sqrt{2}}{7.5\sqrt{1.5}} = \frac{4.5\sqrt{2}}{7.5\sqrt{1.5}} = 0.69$$

$$\frac{A_h}{A} = \frac{4.5}{7.5} = 0.6$$

For $A_h\sqrt{h_1}/A\sqrt{h}$ of 0.69 and A_h/A of 0.6, the *f* from Figure 4-11.3 is 2.4.

$$F = (0.048)(1.0)(2.4) = 0.115 \text{ m}^{1/2}$$

The design fire load (Equation 9) is

$$q = k \cdot \frac{Q}{A_t} = (1.0)\frac{(6 \times 500 \times 17)}{190} = \frac{51{,}000}{190} = 268 \text{ MJ/m}^2$$

Maximum charring rate will be reached at q min (Equation 12)

$$\theta = 0.0175\frac{268 \text{ MJ/m}^2}{0.115 \text{ m}^{1/2}} = 41 \text{ min}$$

The initial charring rate (Equation 13) will be

$$\beta_0 = 1.25 - \frac{0.035}{0.115 + 0.021} = 1 \text{ mm/min}$$

At 8 min, the char depth (Equation 14) will be

$$X = 1 \times 8 = 8 \text{ mm} \quad \text{for} \quad 0 \le 8 \le \frac{41}{3}$$

The smaller dimension b of the beam is 38 mm. The charring depth criterion $0 < x < b/4$ is $0 < 8 < 9.5$ mm, so Equations 14 and 15 are valid. The ratio of the original dimensions is 25/38 or 6.6. Since 38 mm is less than 80 mm, the multiplying factor (Equation 16) is

$$1.35 - 0.0044(38) = 1.18$$

At 8 min, the uncharred area of the beam will be approximately

$$38 \text{ mm} - 2(8 \text{ mm}) = 22 \text{ mm wide}$$

and

$$250 \text{ mm} - (1.18 \times 8 \text{ mm}) = 240 \text{ mm high}$$

As the charring proceeds after (9.5 mm)/(1 mm/min) or 9.5 min, the *b*/4 criterion of the equations no longer holds. This is because the charring rate increases as the temperature at the center of the beam starts to increase.

Equations for parametric fires are also provided in Eurocode 5. The approach is a simplification of Hadvig's equations. For a period t_0, the parametric charring rate is

$$\beta_{par} = 1.5\beta_0 \frac{5F - 0.04}{4F + 0.08} \tag{17}$$

where

F = F' of Equation 10

b_0 = design charring rate of Eurocode 5

The time period t_0 is

$$\tau_0 = 0.006 \frac{q}{F} \tag{18}$$

where q is the total design load of Equation 9.

At t_0, the char rate decreases to zero at $3t_0$. The maximum charring depth during the fire exposure and the subsequent cooling period is $2b_0t_0$. Equations are valid for F between 0.02 and 0.30 $m^{1/2}$, t_0 of 40 min or less, and char depths less than one quarter of the dimensions. Oleson and König[47] tested glued-laminated beams and found agreement with Hadvig's equations for the wide vertical side of a member. Oleson and König[47] noted that, compared to conditions at standard exposure, the mechanical behavior at natural fire exposure is different due to the changes of temperature in the residual cross section during the cooling period. The influence of elevated temperature is no longer concentrated to the outer layer of the residual cross section.

For situations for which no empirical models exist, solutions may be found by the use of theoretical models. Most theoretical models have the flexibility to be used for any desired fire exposures.

Theoretical Models

Considerable efforts have gone into developing theoretical models for wood charring. Theoretical models allow calculation of the charring rate for geometries other than a semi-infinite slab and for nonstandard fire exposures. Roberts[48] reviewed the problems associated with the theoretical analysis of the burning of wood, including structural effects and internal heat transfer, kinetics of the pyrolysis reactions, heat of reaction of the pyrolysis reactions, and variations of thermal properties during pyrolysis. He considered the major problems to be in the formulation of a mathematical model for the complex chemical and physical processes occurring and in the acquisition of reliable data for use in the model.

Many models for wood charring are based on the standard conservation of energy equation. The basic differential equation includes a term for each contribution to the internal energy balance. An early model for wood charring was given by Bamford et a1.[49] The basic differential equation used by Bamford was

$$c\rho \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial X^2} - q \frac{\partial w}{\partial t} \tag{19}$$

where

K = thermal conductivity

T = temperature (°C)

X = location

w = weight of volatile products per cubic centimeter of wood

t = time

q =heat liberated at constant pressure per gram of volatile material evolved

c = specific heat

r = density

In Equation 19, the term on the left side of the equal sign represents the energy stored at a given location as indicated by the increase or decrease of the temperature with time at that location. The first term on the right side of the equal sign represents the thermal conduction of energy away from or into the given location. The second term on the left side represents the energy absorbed (endothermic reaction) or the energy given off (exothermic reaction) as the wood undergoes pyrolysis or thermal degradation. Numerical solutions using computers are normally used to solve these differential equations.

In Bamford's calculations using Equation 19, the rate of decomposition was given by an Arrhenius equation. The heat of decomposition, q, was the difference between the heat of combustion of the wood and that of the products of decomposition. Thermal constants for wood and char were assumed to be the same, and the total thickness of char and wood was assumed to remain constant.

Thomas50 added a convection term to Bamford's equation to obtain

$$\rho c \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial X^2} + Mc_g \frac{\partial T}{\partial X} - q \frac{\partial w}{\partial t} \tag{20}$$

where

M = local mass flow of pyrolysis gases

c_g = specific heat of the gases

The convection term represents the energy transferred in or out of a location due to convection of the pyrolysis gases through a region with a temperature gradient.

The Factory Mutual Research Corporation model (SPYVAP) includes terms for internal convection of volatiles and thermal properties as functions of temperature and density. It was developed by Kung[51] and later revised by Tamanini.[52] Atreya[53] has further revised this model to include moisture absorption. His energy conservation equation is

$$(\rho_a C_{pa} + \rho_c C_{pc} + \rho_m C_{pm}) \frac{\partial T}{\partial t} = \frac{\partial}{\partial X}\left(K \frac{\partial T}{\partial X}\right) + i\left(1 - j\frac{\rho_c}{\rho_f}\right) \cdot$$
$$M_g \frac{\partial H_g}{\partial X} - \frac{\partial \rho_s}{\partial t}\left[-Q + \left(H_a - H_c \frac{\rho_f}{\rho_w}\right) \Big/ \left(1 - \frac{\rho_s}{\rho_w}\right) - H_g\right]$$
$$- \frac{\partial \rho_m}{\partial t}(-Q_m + H_m - H_g) \qquad (21)$$

where

C_p = specific heat [J/(kgK)]
K = thermal conductivity [W/(m K)]
T = temperature (K)
t = time (s)
X = distance (m)
r = density (kg/m³)
M_g = outward mass flux of volatile gases (kg/m²s)
H = thermal-sensible specific enthalpy (J/ kg)
Q = endothermic heat of decomposition of wood for a unit mass of volatiles generated (J/kg at $T_¥$)
i,j = parameters to simulate cracking, between 0 and 1

Subscripts:

¥ = ambient
w = virgin wood
c = char
g = volatile gases
a = unpyrolyzed active material
m = moisture
f = final value
s = solid wood

Equation 21 is similar to the previous equations except the material has been broken up into its components (wood, water, and char). The parameter j eliminates the convection term if the pyrolysis gases are escaping through cracks or fissures in the wood. The last term represents the heat absorbed with vaporization of the water. The conservation of mass equation is

$$\frac{\partial M_g}{\partial X} = \frac{\partial \rho_s}{\partial t} + \frac{\partial \rho_m}{\partial t} \qquad (22)$$

and ensures that the mass of the gases equals the mass loss due to thermal degradation of the wood and vaporization of the moisture.

As noted before, the decomposition kinetics equation for wood is the Arrhenius equation

$$\frac{\partial \rho_s}{\partial t} = -A \frac{(\rho_s - \rho_f)}{(1 - \rho_f/\rho_w)} \exp(-E/RT) \qquad (23)$$

where

A = frequency factor (1/s)
E = activation energy (J/mole)
R = gas constant

Atreya[53] uses a moisture desorption kinetics equation for vaporization of the water in the wood, which is

$$\frac{\partial \rho_m}{\partial t} = -A_m \rho_m \exp(-E_m/RT) \qquad (24)$$

The CMA model[54] developed for NASA provides good results for oven-dry wood because it includes surface recession. Parker55 has taken char shrinkage parallel and normal to the surface into account in the model. Parker also includes different Arrhenius equations for each of the three major components of wood: (1) cellulose, (2) hemicelluloses, and (3) lignin. There may be not only moisture desorption but also an increase in moisture content behind the char front caused by moisture movement away from the surface.[56] A model of Fredlund[57] includes mass transfer as well as heat transfer and provides for surface recession due to char oxidation. In a model for wood combustion, Bryden[58] modeled the wood pyrolysis kinetics, including tar decomposition, using three competing primary reactions and two secondary reactions. The surface boundary layer includes both char shrinkage and surface recession due to char combustion.

Kanury and Holve[35] have presented dimensional, phenomenological, approximate analytical, and exact numerical solutions for wood charring. Other models include those of Havens,[59] Knudson and Schniewind,[60] Kansa et a1.,[61] Hadvig and Paulsen,[62] and Tinney.[63]

A major issue in the use of the more sophisticated models is the adequacy of the available data to use as input. The thermophysical properties for wood pyrolysis models are discussed by Janssens.[64] While primarily for zone models, there is an ASTM Standard Guide for Data for Fire Models.[65] Wood properties are discussed at the conclusion of this chapter.

Most theoretical models for wood charring not only define the charring rate but also provide results for the temperature gradient. This temperature gradient is important in evaluating the load-carrying capacity of the wood remaining uncharred.

Load-Carrying Capacity of Uncharred Wood

In the standard ASTM E119 test of a wood member, structural failure occurs when the member is no longer capable of supporting its design load. The charring of the wood has reduced the cross-sectional area of the member such that the ultimate capacity of the residual member is exceeded. During the charring of the wood member, the temperature gradient is steep in the wood section remaining uncharred. The temperature at the innermost zone of the char layer is assumed to be 300°C. Because of the low thermal conductivity of wood, the temperature 6 mm inward from the base of the char layer is about 180°C once a quasi-steady-state charring rate has been obtained. Some loss of strength undoubtedly results from elevated temperatures. The peak moisture content occurs where the temperature of the wood is about 100°C, which is about 13 mm from the char base. Schaffer et a1.[66] have combined parallel-to-grain strength and stiffness relationships with temperature and moisture content and the gradients of

temperature and moisture content within a fire-exposed slab to obtain graphs of relative modulus of elasticity, compressive strength, and tensile strength as a function of distance below the char layer. (See Figure 4-11.5.) The temperature profile in a semi-infinite wood slab can be expressed as an exponential term or a power term.[67] An equation based on a power term is

$$T = T_i + (300 - T_i)\left(1 - \frac{x}{d}\right)^2 \tag{25}$$

where

T = temperature (°C)

T_i = initial temperature (°C)

x = distance from the char front (mm)

d = thermal penetration depth (mm)

In the tests of White,[31] an average value for the thermal penetration depth was 33.[67] Based on European tests, a more conservative value of 40 was recommended for the thermal penetration depth.[67] The power term does not provide for the plateau in temperatures that often occurs at 100°C in moist wood. The power term has also been used to estimate the temperature profile in wood exposed to a constant heat flux.[41] The theoretical models discussed previously can be used to determine the temperature gradient within the wood remaining uncharred.

There are two approaches to evaluating the load-carrying capacity: to evaluate the remaining section either as a single homogeneous material or as a composite of layers or elements with different properties. In the single homogeneous material approach, one uses either reduced material properties or the room temperature material properties. A greater reduction in cross sectional area is calculated if the material properties are not reduced.

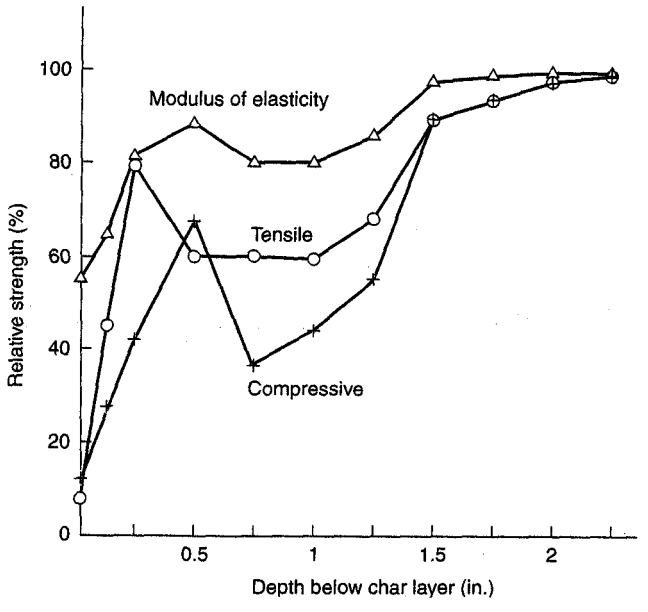

Figure 4-11.5. ***Relative modulus of elasticity and compressive and tensile strength as a function of distance below char layer in softwood section under fire exposures. (Expressed in percent of that at 25°C and initial moisture content of 12 percent). Duration of fire exposure should be equal to or greater than 20 min to apply results of this figure.***

Empirical a Models

One common approach in accounting for the loss in strength in the section remaining uncharred is to assume that the strength and stiffness of the entire uncharred region are fractions a of their room temperature values.

For bending rupture of a beam, an equation of this type would be

$$\frac{M}{S(t)} = \alpha\sigma_0 \tag{26}$$

where

M = applied moment (design load)

S = section modulus of charred member

s_0 = modulus of rupture at room temperature

t = time

Assuming the residual cross-section is rectangular in shape before and during fire exposure, the section modulus of the charred member is[68]

$$S(t) = \frac{1}{6}\left[(B - 2C_1t)(D - jC_2t)^2\right] \tag{27}$$

where

B = original breadth of beam

D = original depth of beam

C_1 = charring rate in breadth direction

C_2 = charring rate in depth direction

j = 1 for three-sided fire exposure or 2 for four-sided fire exposure (Figure 4-11.6)

Alternative to Equations 22 and 23 are the following, Equations 28 through 30:

$$\frac{k}{\alpha}\frac{B/D}{[d/D - (1 - B/D)]} = \left(\frac{d}{D}\right)^2 \tag{28}$$

for exposure on all four sides,[69] and

$$\frac{k}{\alpha}\frac{B/D}{[B/D - 2(1 - d/D)]} = \left(\frac{d}{D}\right)^2 \tag{29}$$

for exposure on three sides,[70,71]

where

k = load, as fraction of room temperature ultimate load of original member

d = critical depth of the uncharred beam

The fire resistance is equal to the time to reach the critical depth, or

$$t = (D - d)/jC \tag{30}$$

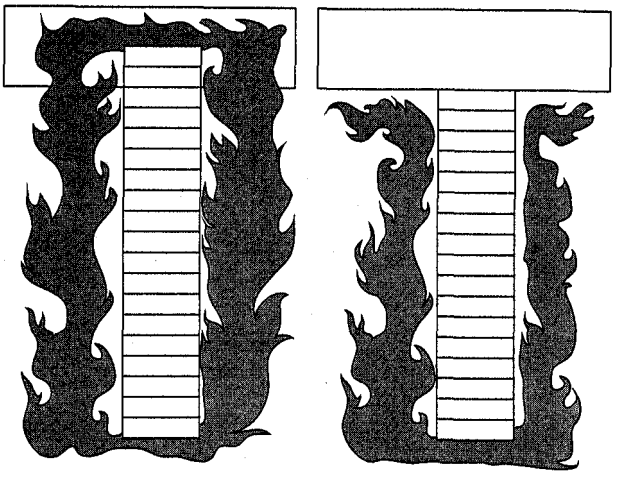

Figure 4-11.6. ***Fire exposure of beams on three or four sides.***

Proposed a values ranged from 0.5 in New Zealand to 0.83 in France.[68] The differences in a values are due to uncertainty, differences in design load, and desired level of safety. The application of the above equations is generally limited to large wood members. In light-frame members, a values would be substantially lower.[72] In Eurocode 5, this approach is called the "reduced strength and stiffness method." The reduction factors are a function of the perimeter of the fire-exposed residual cross section divided by the area of the cross section.

In addition to bending rupture, the fire resistance of a beam may depend on lateral buckling of the beam.[69] Similar expressions can be developed for columns and tension members.[68,70-71,73] Reviews of fire resistance design methodologies for large wood members include those of Schaffer,[68] Pettersson,[74] and Barthelemy and Kruppa.[75] Kirpichenkov and Romanenkov[76] discussed the calculation procedures in the Soviet Union. The fire resistance of wood structures is also briefly discussed by Odeen.[77]

In developing a model for fire-exposed unprotected wood joist floor assemblies, Woeste and Schaffer[78,79] evaluated various time-dependent geometric terms that could be used to modify the strength reduction factor, a. The selected term was

$$\alpha = \frac{1}{1 + (B + 2D/BD)\gamma t_f} \tag{31}$$

where

t_f = failure time

g = empirical thermal degrade parameter

The model has been experimentally evaluated,[80,81] extended to floor-truss assemblies,[79,82] and used as part of a first-order second-moment reliability analysis of floor assemblies.[78,79] Reliability-based design of the fire endurance of light-frame construction is also discussed by Lau and Barrett.[72] In a model for metal plate-connected wood trusses,[83] the strength degradation factors for the wood are calculated as a function of the duration of exposure and the temperature profile within the wood component.

Effective Cross-Sectional Area Method

For a second approach, an equivalent zero-strength layer, 6, was calculated and the rest of the member is evaluated using room temperature property values. In the model of Schaffer and others[66] for beams, the 6 was estimated to be 8 mm (0.3 in. thick). This zero-strength layer, 6, was added to the char depth, b*t*, to obtain the total zero-strength layer. This zero-strength layer model was incorporated within a reliability-based model to predict the strength of glued-laminated beams with individual laminates of various grades of lumber.[84] This zero-strength layer approach is called the "effective cross-section method" in Eurocode 5. In Eurocode 5,6 is 7 mm after 2 min (linear fraction of 7 mm up to 20 min). In Technical Report 10 of the American Wood Council,[85] a 20 percent increase in the charring rate is used.

Performance of the structural member in a fire will depend on the ratio of the applied load to the ultimate capacity of the residual member. Calculations of the structural capacity of the remaining cross section are normally made using ultimate strength values. Information on obtaining estimates for average ultimate values from allowable design values can be found in Technical Report 10. Examples of the structural calculations and load ratio tables are also provided. Design or characteristic strength values are used in the Eurocode 5 calculations. Design methods account for the various factors affecting performance in different manners. Care must be taken to ensure that all the design values and the methodologies are compatible.

For fire-damaged members, Williamson[86] recommended 6 of 6 mm (0.25 in.) for designs controlled by compression (16 mm [0.625 in.] if design is controlled by tension) and the use of 100 percent of the original basic allowable stresses in calculation of load capacity.

Composite Models

The most complex approach to evaluating the fire endurance of a wood member is to assume that the uncharred region consists of layers or elements at different temperatures and moisture contents. The strength and stiffness properties are dependent on the temperature and moisture content profiles. These are referred to as *general calculation methods* in Eurocode 5. In one model with layers, the compressive and tensile strengths and modulus of elasticity of each layer are assumed to be fractions of the room temperature values. Using one 38-mm (1.5-in.) heated layer with reduced properties, Schaffer et al.[66] analyzed a beam using transformed section analysis. In the similar elastic transformed section model of King and Glowinski,[87] the heated zone of the remaining wood section is divided into two layers at elevated temperatures. Transformed section analysis is also used by Lee-Gun Kim and Jun-Jae Lee[88] and by Janssens.[89] A finite difference model for wood beams and columns was developed by Tavakkol-Khah and Klingsch.[90]

Do and Springer[91-93] proposed a fire resistance model for wood beams based on mass loss versus strength data.

The work included a program to predict the temperatures and mass loss within the wood member. The input data came from small-scale tension, compression, and shear tests done on specimens that had previously been heated in a muffle oven.

One-Hour Fire-Resistive Exposed Wood Members

Lie[70] developed simple formulas for calculating the fire resistance of large wood beams and columns based on theoretical studies involving experimental data and equations similar to Equations 26 through 30. These formulas are recognized by the building codes in the United States and Canada. The methodology is discussed in wood industry publications.[94,95] These formulas give the fire resistance time, *t*, in minutes, of a wood beam or column with minimum nominal dimension of 152 mm (6 in.). The net finish width for a nominal 152-mm (6-in.) glued-laminated member is 130 mm (5 1/8 inches).

For beams, the equations are

$$t = 2.54ZB\left[4 - 2\left(\frac{B}{D}\right)\right] \quad \text{for fire exposure on four sides} \tag{32}$$

$$t = 2.54ZB\left[4 - \left(\frac{B}{D}\right)\right] \quad \text{for fire exposure on three sides} \tag{33}$$

where

B = width (breadth) of a beam before exposure to fire (in.)

D = depth of a beam before exposure to fire (in.)

Z = load factor (See Figure 4-11.7.)

For columns, the equations are

$$t = 2.54ZD\left[3 - \left(\frac{D}{B}\right)\right] \tag{34}$$

for fire exposure on four sides

$$t = 2.54ZD\left[3 - \left(\frac{D}{2B}\right)\right] \tag{35}$$

for fire exposure on three sides

where

B = larger side of a column (in.)

D = smaller side of a column (in.)

The 2.54Z factor in the above equations is 0.10Z for SI units of mm. For columns, the load factor, Z (see Figure 4-11.7) includes the effect of the effective length factor, K_e, (see Figure 4-11.8) and the unsupported length of the column, **l**. Currently, the codes do not permit the wide side of the column to be the unexposed face (Equation 34). The full dimensions of the column are used even if the column is recessed into a wall.

Connectors and fasteners relating to support of the member must be protected for equivalent fire-resistive construction. Where minimal 1-hr fire endurance is required, connectors and fasteners must be protected from fire exposure by 38 mm (1 1/2 in.) of wood, appropriate

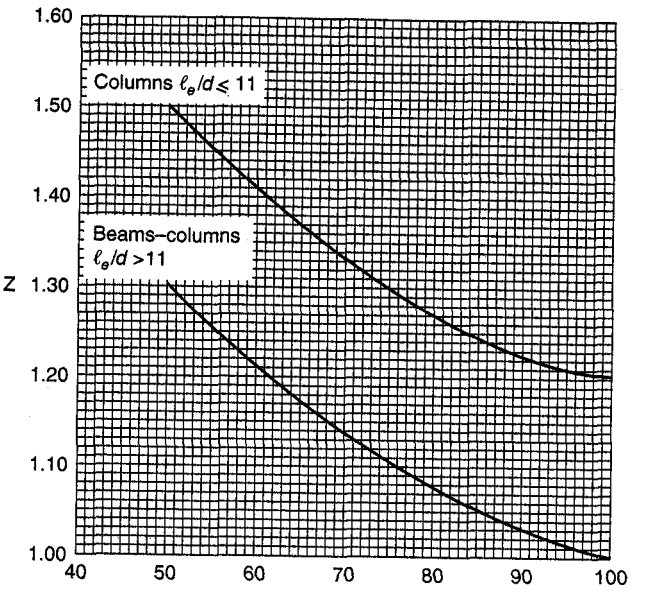

Figure 4-11.7. ***Load factor versus load on member as percent of allowable. (NBCC uses 12 instead of 11 as criterion for two curves.) Effective column length, l_e, is equal to K_el (Fig. 4-11.8) and d is cross-sectional dimension in plane of lateral support,***

thickness of fire rated gypsum board, or any coating approved for a 1-hr rating. The American Forest & Paper Association publication94 on the procedure includes diagrams giving typical details of such protection. Carling[96] summarized work done in Europe on the fire resistance of joint details in load-bearing wood construction. Eurocode 5 also includes information on calculating the fire endurance of connections and protecting connections in fire-rated timber members.

There is often a high-strength tension laminate on the bottom of glued-laminated timber beams. As a result, it is required that a core lamination be removed, the tension zone moved inward, and the equivalent of an extra nominal 51-mm- (2-in.-) thick outer tension lamination be added to ensure that there is still a high-strength laminate left after fire exposure.

EXAMPLE 3:

Determine the fire resistance rating for a 5 1/8-in. × 21-in. (130-mm × 533-mm) beam exposed to fire on three sides and loaded to 75 percent of its allowable load.

$$D = 21 \text{ in.}$$

$$B = 5.125 \text{ in.}$$

From Figure 4-11.7, *Z* for beam loaded to 75 percent of allowable is 1.1. From Equation 33,

$$t = 2.54(1.1)(5.125)([4 - (5.125/21)]$$

$$t = 53.8 \text{ min}$$

The methodology of this section has building code recognition in the United States and Canada but is only applic-

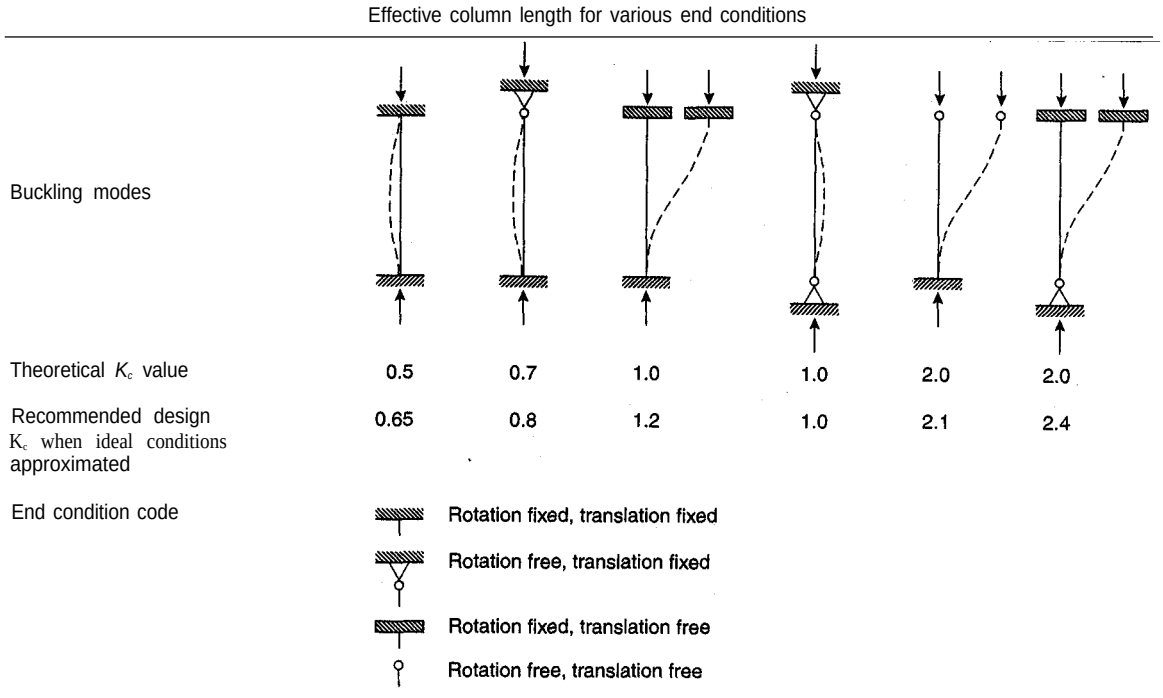

Figure 4-11.8. ***Effective column length.***

able to large wood beams and columns. There is no recognized procedure for solid wood floors or roofs. Possible methodologies for the structural analysis of these timber decks can be found in Technical Report 10,[85] in an article by Janssens,[89] and in Eurocode 5. A methodology for estimating the times for thermal failure is in Eurocode 5. The method is based on the design charring rates and a reduction coefficient for the joints in the timber decks.[89]

Property Data

Proper input data are critical to the use of any model. For the models discussed in this section, property data include strength and stiffness properties and thermal properties. Property data for wood can be found in the various chapters of Wood Handbook: *Wood as an Engineering Material*[32] (available as pdf files from www.fpl.fs.fed.us). A chapter on fire safety is also in the *Wood Handbook*. Equations and graphs of the strength and stiffness of wood as functions of temperature and moisture content are available.[97-99] Recent research in the development of fire endurance models has provided additional data specific for application to such models. An extensive study on fire-exposed wood in tension was done by Lau and Barrett.[100] Thermal properties can also be found in the various references for charring models, Annex E of Eurocode 5, and in other sources.[64,65,101]

While it is often less complicated to assume constant property values, these properties are very often a function of other properties or factors. Most wood properties are functions of density, moisture content, grain orientation, and temperature. Chemical composition may also be a factor. Since an understanding of these factors is important to the application of property data, the factors are defined in the rest of this section.

The oven-dry density of wood can range from 160 kg/m^3 (10 lb/ft^3) to over 1040 kg/m^3 (65 lb/ft^3), but most species are in the 320 to 720 kg/m^3 (20 to 45 lb/ft^3) range.[32] The density of wood relative to the density of water (i.e., specific gravity) is normally based on the oven-dry weight and the volume at some specified moisture content, but in some cases the oven-dry volume is used. As the empirical equations for charring rate show, the materials with higher density have slower char rate.

Wood is a hygroscopic material, which gains or loses moisture depending upon the temperature and relative humidity of the surrounding air. Moisture content of wood is defined as the weight of water in wood divided by the weight of oven-dry wood. Green wood can have moisture content in excess of 100 percent. However, air-dry wood comes to equilibrium at moisture content less than 30 percent. Thirty percent moisture content is also considered the approximate moisture content at which the cell walls are saturated with water but there is no water in the cell lumens. This condition is known as the *fiber* saturation point. At higher moisture contents, water exists in the cell lumens. Many physical and mechanical properties of wood only change with moisture content at moisture contents below the fiber saturation point. Under the conditions stated in ASTM E119 (23°C, 50 percent relative humidity), the equilibrium moisture content is 9 percent. Moisture generally reduces the strength of wood but also reduces the charring rate.

Both density and moisture content affect the thermal conductivity of wood. The average thermal conductivity perpendicular to the grain is[32]

$$k = S(0.0001941 + 0.000004064M) + 0.01864 \quad (36)$$

where

k = thermal conductivity (W/m·K)

S = density based on volume at current moisture content and oven-dry weight (kg/m³)

M = moisture content (percent)

The above equation is valid for moisture contents of 25 percent or less, densities greater than 300 kg/m³, and temperature of 24°C. Conductivity increases about 2 to 3 percent per 10°C.[32]

The fiber (grain) orientation is important because wood is an orthotropic material. The longitudinal axis is parallel to the fiber or grain. The two transverse directions (perpendicular to the grain) are the radial and tangential axes. The radial axis is normal to the growth rings, and the tangential axis is tangent to the growth rings. For example, the longitudinal strength properties are usually about 10 times the transverse properties, and the longitudinal thermal conductivity is 1.5 to 2.8 times the transverse property.

In fire-resistance analysis, temperature can have a significant influence on the properties of wood. The preponderance of property data is often limited to temperatures below 100°C. The effect of temperatures on the strength properties of wood is shown in Figures 4-11.9 through 4-11.11. The heat capacity, c_p, (kJ/kg·K) of dry wood is approximately related to temperature, t, in K) by32

$$c_p = 0.1031 + 0.003867t \quad (37)$$

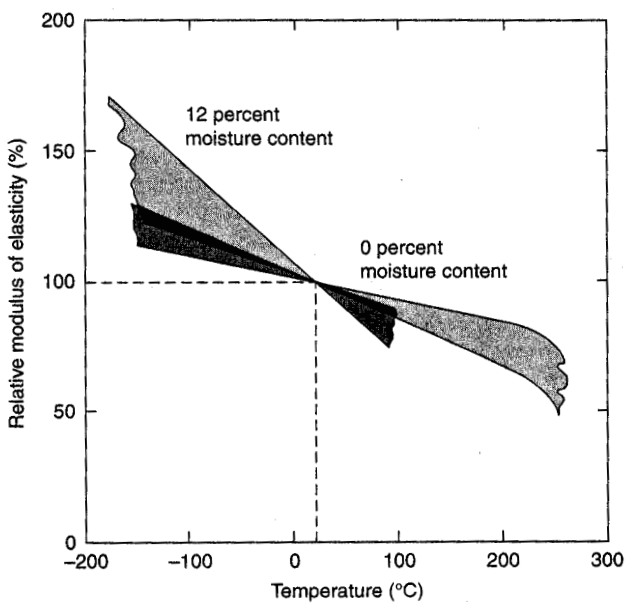

Figure 4-11.9. ***The immediate effect of temperature on modulus of elasticity parallel to the grain at two moisture contents relative to value at 20°C. The plot is a composite of results from several studies. Variability in reported trends is illustrated by the width of bands.[32]***

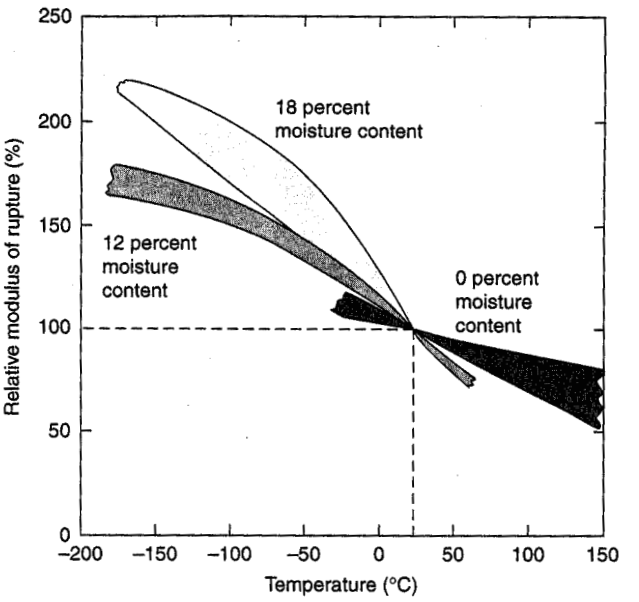

Figure 4-11.10. ***The immediate effect of temperature on modulus of rupture in bending at three moisture contents relative to value at 20°C.[32]***

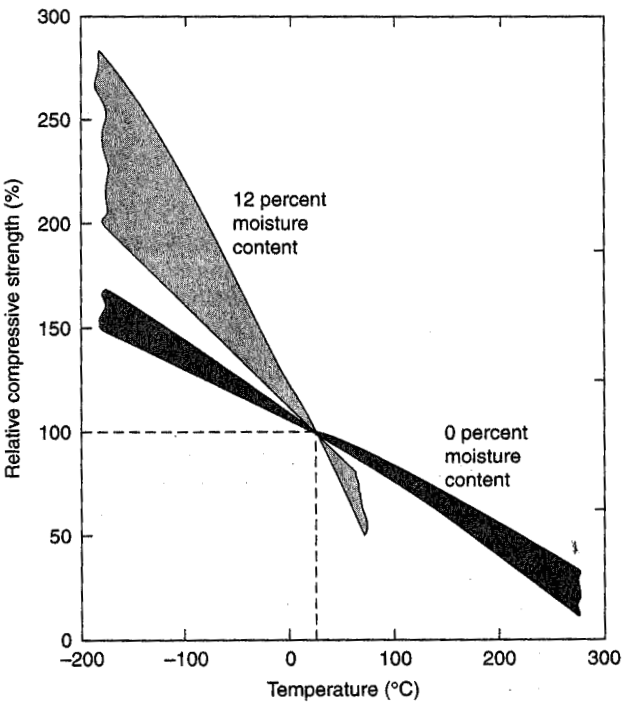

Figure 4-11.11. ***The immediate effect of temperature on compressive strength parallel to the grain at two moisture contents relative to the value at 20°C.***

For moist wood below the fiber saturation point, the heat capacity is the sum of the heat capacity of dry wood and that of water and an additional adjustment factor for the wood–water bond.[32]

The major components of wood are cellulose, lignin, hemicelluloses, extractives, and inorganic materials (ash). Softwoods have lignin contents of 23 to 33 percent, while hardwoods have only 16 to 25 percent. The types and amounts of extractives vary. Cellulose content is generally around 50 percent by weight. The component sugars of the hemicelluloses are different for the hardwood and softwood species. Chemical composition can affect the kinetics of pyrolysis (Equation 23) and the percentage weight of the residual char. In the degradation of wood, higher lignin content results in greater char yield.

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