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ANALYTICAL METHODS FOR DETERMINING FIRE RESISTANCE OF TIMBER MEMBERS

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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 E 119.[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, reduction in member spacing, and thicker protection layers, without reducing the listed rating. Two fire-endurance design procedures for wood that allow greater flexibility have U.S. and Canadian building code acceptance. 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, and
3. Load-carrying capacity of the remaining uncharred portions of the structural wood elements.

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.[4] 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. 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 Calculation Procedure

The component additive calculation procedure is a method to determine conservatively the fire resistance ratings of load-bearing light-frame wood floor and roof assemblies and of load-bearing and nonload-bearing 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 for the individual layers and the times assigned to the framing. The procedure was developed by the National Research Council of Canada (NRCC), and has gained code approval in both the U.S. and Canada.

The times assigned to the protective membranes (Table 4-11.1), the framing (Table 4-11.2), and other factors (Table 4- 11.3) are added together to obtain the fire resistance rating for the assembly. The times are based on empirical correlation with actual ASTM E 119 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 times assigned to the protective membranes are not the "finish ratings" of the material cited in test reports or listings. [A finish rating is defined as the time to reach either an average temperature rise of 250°F (139°C) or a maximum rise of 325°F (181°C), on the unexposed side of the material.] The building codes include requirements for fastening the protective membranes to the frame. The addition of insulation to a wall

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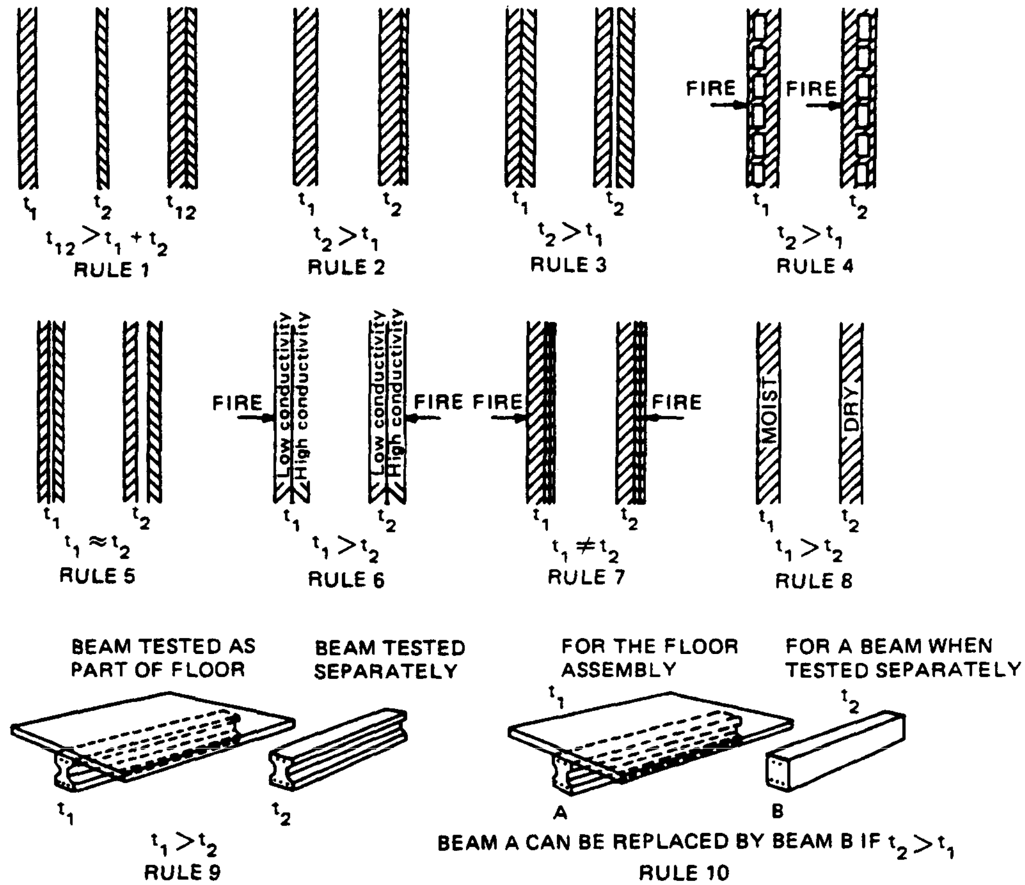

Fig. 4-11.1. Harmathy's ten rules of fire endurance.[4]

assembly can increase its fire resistance. (See Table 4-11.3.) Adding insulation to a floor or roof assembly cars 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 (Tables 4- 11.4 and 4- 11.5), in order to ensure that the wall or floor/roof assembly does not fail because of fire penetration or heat transfer

TABLE 4-11.1 ***Time Assigned to Protective Membranes*†***

Description of Finish	Time (min.)
3/8-in. Douglas fir plywood, phenolic bonded	5
1/2-in. Douglas fir plywood, phenolic bonded	10
5/8-in. Douglas fir plywood, phenolic bonded	15
3/8-in. gypsum board	10
1/2-in. gypsum board	15
5/8-in. gypsum board	20
1/2-in. type X gypsum board	25
5/8-in. type X gypsum board	40
Double 3/8-in. gypsum board	25
1/2-in. + 3/8-in. gypsum board	35
Double 1/2-in. gypsum board	40
Double 1/2-in. gypsum board‡	50

*On walls, gypsum board must be installed with the long dimension parallel to framing members, with all joints finished. However, 5/8-in. type X gypsum board may be installed horizontally with the horizontal joints unsupported.
†On floor/ceiling or roof/ceiling assemblies, gypsum board must be installed with the long dimension perpendicular to framing members, and must have all joints finished.
‡Wire mesh with 0.06-in.-diameter wire and 1-sq-in. openings must be fastened between the two sheets of gypsum board.

TABLE 4-11.2 ***Time Assigned for Contribution of Wood Frame****

Description of Frame	Time Assigned to Frame (min.)
Wood studs, 16 in. on center	20
Wood floor and roof joists, 16 in. on center	10
Wood roof and floor truss assemblies, 24 in. on center	5

*Minimum size for studs is nominal 2 in. by 4 in.. Wood joists and members of trusses also must not be less than nominal 2 in. by 4 in. The listing for truss assemblies does not apply to trusses with metal-tube or bar webs. The spacing between studs or joists should not exceed 16 in. on center. The spacing between trusses should not exceed 24 in. on center.

TABLE 4-11.3 ***Time Assigned for Additional Protection***

Description of Additional Protection	Time Assigned to Insulation (min.)
Adds to the fire endurance rating of wood stud walls if the spaces between the studs are filled with rock wool or slag mineral wool batts weighing not less than ¼ lb/sq ft of wall surface.	15
Adds to the fire endurance rating of nonload-bearing wood stud walls if the spaces between the studs are filled with glass fiber batts weighing not less than ¼ lb/sq ft of wall surface.	5

through the assembly. Instead of being one of the combinations listed in Tables 4-11.4 and 4-11.5, the membrane on the side not exposed to fire (the outside or top) may be any membrane listed in Table 4-11.1 with an assigned time of 15 min. or greater.

The component additive calculation procedure is in the *Supplement to the National Building Code of Canada* (SNBCC)[5] and some U.S. building codes. The application of the method is generally limited to 60 or 90 min. The tables presented in this chapter are based on publications of the American Forest & Paper Association[6] and the Canadian Wood Council.[7] For specific situations, the applicable building code should be checked for acceptance of, modifications to, and limitations on the procedure as presented in this chapter. There are differences between the codes in what is accepted. There are individual items in the tables that are not accepted by all the codes that otherwise accept the procedure.

TABLE 4-11.4 ***Alternative Membranes on Face of Wood Stud Walls Not Exposed to Fire (Exterior)****

Sheathing	Paper	Exterior Finish
⅝-in. tongue-and-groove lumber		Lumber siding
5/16-in. exterior-grade plywood	Sheathing paper	Wood shingles and shakes
½-in. gypsum board		¼-in. exterior-grade plywood ¼-in. hardboard Metal siding Stucco on metal lath Masonry veneer
None	None	⅜-in. exterior-grade plywood

*Membrane may be any combination of sheathing, paper, and exterior finish in table or any other membrane listed at 15 min. or greater in Table 4-11.1.

The component additive calculation procedure 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 (2-in. × 4-in. studs, 16 in. on center) with ⅝-in. Douglas fir phenolic-bonded plywood over ½-in. type X gypsum wallboard on the side exposed to fire with fiberglass insulation in the cavity is:

From Table 4-11.1:	
⅝-in. Douglas fir plywood, phenolic bonded	15 min.
½-in. type X gypsum board	25 min.
From Table 4-11.2:	
Wood stud framing	20 min.
Calculated rating (total)	60 min.

The fiberglass insulation provides no additional fire resistance time for a load-bearing wall. The other side of the exterior wall, if it has no fire resistance requirement, can be ⅜-in. exterior-grade plywood (Table 4-11.3) or any panel with an assigned time of 15 min. (Table 4-11.1).

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. Both for fire-retardant coatings and fire-resistive coatings, the performance as a fire resistant membrane on wood has been evaluated.[8-10] Tests on coated timber members have also been reported in Finland and U.S.S.R.[11]

There is limited published data on the protection provided by directly covering a wood member with gypsum board or other nonwood panel products. Finish ratings listed for panel products used in ASTM E 119 tests of assemblies have been used to estimate the delay in the onset of char formation provided by the panel product. Gardner and Syme[12] found that gypsum board not only delayed the onset of char formation but also reduced the subsequent rate of char formation. In their two-hour tests, ½-in.-thick gypsum board on wood beams reduced the depth of char by approximately

TABLE 4-11.5 ***Flooring or Roofing over Wood Framing****

Assembly	Subfloor or Roof Deck	Finish Flooring or Roofing
Floor	½-in. plywood or 11/16-in. tongue-and-groove softwood lumber	Hardwood or softwood flooring on building paper; or Resilient flooring, parquet floor, felted-synthetic-fiber floor coverings, carpeting, or ceramic tile on ⅜-in.-thick panel-type underlay; or Ceramic tile on 1¼-in. mortar bed.
Roof	½-in. plywood or 11/16-in. tongue-and-groove softwood lumber	Finish roofing material with or without insulation

*Upper membrane consists of a subfloor and finish floor, roof deck and roofing, or any other membrane listed at 15 min. or greater in Table 4-11.1.

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[13] developed a one-dimensional finite difference model and computer program for thermal analysis of construction walls. Gammon[14] developed a two-dimensional finite element heat transfer model for wood stud wall assemblies. Difficulties in modeling the charring of wood and the physical deterioration of the panel products complicate these numerical methodologies. New models are being developed in North America, Sweden, New Zealand,[15] and Australia.

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 articles by Browne,[16] Schaffer,[17,19] Hall *et al.* [18] and Hadvig.[20] 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.

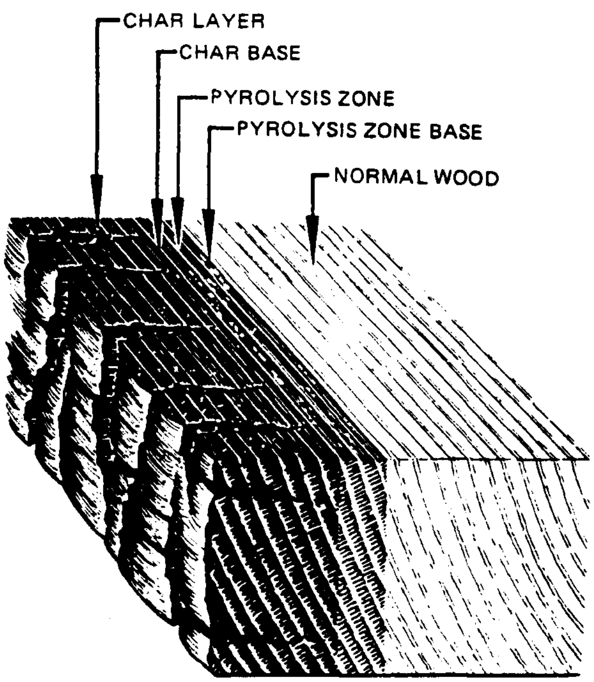

Fig. 4-11.2. Degradation zones in a wood section.

Establishing the charring rate is critical to evaluating fire resistance, because char has virtually no load-bearing capacity. There is a fairly distinct demarcation between char and uncharred wood. The base of the char layers is wood reaching a temperature of approximately 290°C (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.

EMPIRICAL MODELS

Standard ASTM E 119 Fire Exposure

Expressions for charring rate in the standard ASTM E 119 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 ½ 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. (See also reference 21.)

Schaffer[22] reported transverse-to-grain charring rates as a function of density and moisture content for white oak. Douglas fir, and southern pine. The regression equations for B (min. per in., the reciprocal of charring rate) were

$$B = 2[(28.726 + 0.578M)\rho + 4.187] \quad \text{for Douglas fir} \qquad (1)$$

$$B = 2[(5.832 + 0.120M)\rho + 12.862] \quad \text{for southern pine} \qquad (2)$$

$$B = 2[(20.036 + 0.403M)\rho + 7.519] \quad \text{for white oak} \qquad (3)$$

where

M = percent moisture content, and
ρ = dry specific gravity.

White[23] developed an empirical model based on eight species. The char rate equation was of the form

$$t = mx_c^{1.23} \qquad (4)$$

where

t = time (min.),
m = char rate coefficient, and
x_c = char depth (mm).

The char rate coefficient could be estimated with the equation

$$m = -0.147 + 0.000564\rho + 0.0121u + 0.532f_c \qquad (5)$$

where

ρ = oven-dry density (kg/m^3),
u = moisture content (percent), and
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).

Recent char rate experiments have been reported in Australia,[12] Europe,[24] and New Zealand.[25]

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[26] suggest the model

$$\frac{\ell}{t} \approx \left(\frac{2}{a}\right)\left(1 - \frac{b\ell}{a}\right) \tag{6}$$

where

ℓ = thickness of slab,
t = fire endurance time, and
a,b = constants.

They consider the $(2/\alpha)$ 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[27] provided the equation

$$b_m = 1.128t + 0.0088t^2 \tag{7}$$

where

b_m = contribution to fire resistance (min.), and
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 charring rate parallel to the grain of wood is approximately twice that transverse to the grain.[18] As a beam or column chars, the corners become rounded. The rounding is generally considered to have a radius equivalent to the char depth on the sides.

In Europe, structural Eurocodes are being developed for the design of structures. As currently written, the draft of Eurocode 5 (Timber Structures), Part 1.2 on structural fire design is largely based on calculation methods.[28] Specific design values for char rate are included in the document.

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.[29]

Nonstandard Fire Exposures

The above equations were stated to apply to the standard ASTM E 119 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). As a result of increased testing with heat release rate calorimeters, char rate data as a function of external heat flux are becoming available.[30-32]

Hadvig[20] 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

$$q = k \cdot \frac{Q}{A_t} \tag{8}$$

where

q = design fire load (MJ/m^2);
k = transfer coefficient (dimensionless);
Q = sum of the products of mass and lower calorific value of materials to be found in the compartment (MJ); and
A_t = total internal area of the compartment, including floor, walls, ceiling, windows, and doors (m^2).

The transfer coefficients are given in Table 4-11.6 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

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

where

F' = geometrical opening factor (m$^{1/2}$),
A = total area of windows, doors, and other openings in walls (i.e., vertical openings only) (m^2), and
h = weighted mean value of the height of vertical openings, weighted against the area of the individual openings (m).

TABLE 4-11.6 *The Transfer Coefficient, k*[20,33]

Type of fire compartment*	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†	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: (*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/m^3).
D: 50 pct concrete, 50 pct gas concrete (density 500 kg/m^3).
E: 50 pct gas concrete (density 500 kg/m^3), 33 pct concrete, and 17 pct laminate consisting of (taken from the inside) 13-mm plasterboard (density 500 kg/m^3), 10-cm mineral wool (density 50 kg/m^3), and brick (density 1,800 kg/m^3).
F: 80 pct steel plate, 20 pct 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 pct concrete and 80 pct laminate consisting of a double plasterboard (2 × 13 mm) (density 790 kg/m^3), 10-cm air space, and another double plasterboard (2 × 13 mm) (density 790 kg/m^3).
H: Steel plate on either side of 100-mm mineral wool (density 50 kg/m^3).
†The higher values apply to q < 60 MJ/m; the lower values apply to q > 500 MJ/m^2. Intervening values are found by interpolation.

The design opening factor is

$$F = F' \cdot k \cdot f \tag{10}$$

where

F = design opening factor ($m^{1/2}$),
F' = geometrical opening factor ($m^{1/2}$),
k = transfer coefficient of bounding structure (dimensionless), and
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[20] equations are

$$\theta = 0.0175\frac{q}{F} \tag{11}$$

$$\beta_0 = 1.25 - \frac{0.035}{F+0.021} \quad \text{for } 0.02 \le F \le 0.30 \tag{12}$$

$$X = \beta_0 \cdot \tau \quad \text{for } 0 \le \tau \le \frac{\theta}{3} \tag{13}$$

$$X = \beta_0\left(-\frac{1}{12}\theta + \frac{3}{2}\tau - \frac{3}{4}\frac{\tau^2}{\theta}\right) \quad \text{for } \frac{\theta}{3} \le \tau \le \theta \tag{14}$$

where

θ = time at which maximum charring is reached for the values used for F and q (min.),
β_0 = initial value of rate of charring (mm/min.),
X = charring depth (mm),
F = design opening factor ($m^{1/2}$) (defined in Equation 10),
q = design fire load (MJ/m^2) (defined in Equation 8), and
τ = time (min.).

These equations are valid for fire exposures less than 120 min. and 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 11 and 12 are therefore modified for faster char rate β_0 is 50 percent higher), shorter time is allowed for maximum charring (θ is cut in half), and Equation 13 is applicable for $\tau < \theta$.[20]

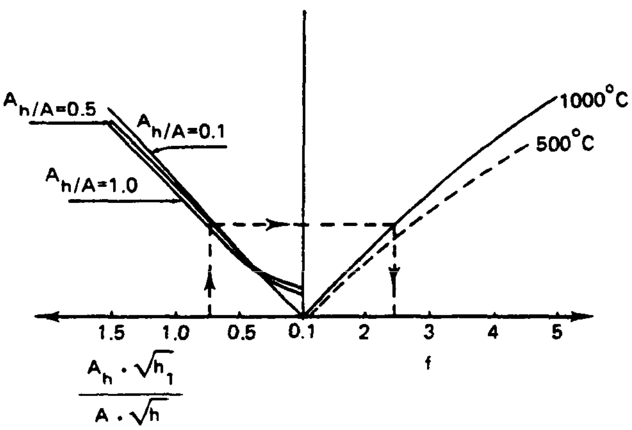

Fig. 4-11.3. Diagram for the determination of f for fire temper-

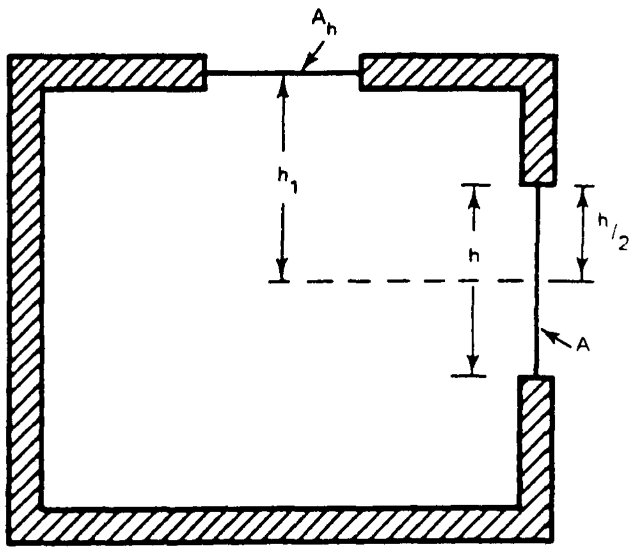

Fig. 4-11.4. Simplified sketch of vertical cross section of ventilated compartment with notation.[20]

Equations 11 through 14 are for glued timber with a density of 470 kg/m^3 including a moisture content of 10 percent and minimum width of 80 mm or greater or square members of minimum 50 × 50 mm. Equations 13 and 14 are valid only for $0 < X < b/4$, where b is the dimension of the narrow face of a rectangular member. For 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 13 or 14 times the dimensionless quantity

$$1.35 - 0.0044(b) \tag{15}$$

where

b = dimension of narrow face (mm).

EXAMPLE 2:

The room is a standard fire compartment consisting of brick, concrete, and gas concrete. The floor area is 5 × 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 × 3 m. The skylight is 2 m above the midheight of the windows. The fire load is 6 m^3 of wood.

Assuming a fire temperature of 1000°C, a wood density of 500 kg/m^3, 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 9) 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 10) is

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

The k is obtained from Table 4-11.6 (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 8) 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 will be reached at θ min. (Equation 11).

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

The initial charring rate (Equation 12) will be

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

At 8 min., the char depth (Equation 13) will be

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

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 13 and 14 are valid. The ratio of the original dimensions is 25/3.8 or 6.6. Since 38 mm is less than 80 mm, the multiplying factor (Equation 15) 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.

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.

Oleson and Konig[34] 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.

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. Unfortunately, no completely satisfactory model has yet been developed. Roberts[35] 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 al.* [36] The basic differential equation used by Bamford was

$$c\rho\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial X^2} - q\frac{\partial w}{\partial t} \qquad (16)$$

where

K = thermal conductivity,
T = temperature,
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, and
ρ = density.

In Equation 16, 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 16, 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.

Thomas[37] added a convection term to Bamford's equation to obtain

$$\rho c\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial X^2} + Mc_g\frac{\partial T}{\partial X} - q\frac{\partial w}{\partial t} \qquad (17)$$

where

M = local mass flow of pyrolysis gases, and
c_g = specific heat of the gases.

The convection term represents the energy transferred in or out of a location as a result of the 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[38] and later revised by Tamanini.[39] Atreva[40] has further revised this model to include moisture absorption. His energy conservation equation is

$$(\rho_a C_{pa} + \rho_c C_{pc} + \rho_m C_{pm})\frac{\partial T}{\partial t} = \frac{\partial}{\partial X}\left(K\frac{\partial T}{\partial X}\right) + i\left(1 - j\frac{\rho_c}{\rho_f}\right) \cdot M_g\frac{\partial H_g}{\partial X} - \frac{\partial \rho_s}{\partial t}\left[-Q + \left(H_a - H_c\frac{\rho_f}{\rho_w}\right)\Big/\left(1 - \frac{\rho_s}{\rho_w}\right) - H_g\right] - \frac{\partial \rho_m}{\partial t}(-Q_m + H_m - H_g) \tag{18}$$

where

C_p = specific heat [J/(kg K)],
K = thermal conductivity [W/(m K)],
T = temperature (K),
t = time (s),
X = distance (m),
ρ = density (kg/m^3),
M_g = outward mass flux of volatile gases (kg/m^2 s),
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_∞), and
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, and
s = solid wood.

Equation 18 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

$$\frac{\partial M_g}{\partial X} = \frac{\partial \rho_s}{\partial t} + \frac{\partial \rho_m}{\partial t} \tag{19}$$

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

$$\frac{\partial \rho_s}{\partial t} = -A\frac{(\rho_s - \rho_f)}{\left(1 - \frac{\rho_f}{\rho_w}\right)}\exp(-E/RT) \tag{20}$$

where

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

Atreya[40] uses a moisture desorption kinetics equation for vaporization of the water in the wood, which is

$$\frac{\partial \rho_m}{\partial t} = -A_m\rho_m\exp(-E_m/RT) \tag{21}$$

Parker[41] 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) hemicellulose, and (3) lignin.

Kanury and Holve[26] have presented dimensional, phenomenologlcal, approximate analytical, and exact numerical solutions for wood charring. Other models include those of Havens,[42] Knudson and Schniewind,[43] Kansa *et al,*[44] Hadvig and Paulsen,[45] and Tinney.[46]

Moisture resorption and surface recession were not considered until recently. There may be not only moisture resorption but also an increase in moisture content behind the char front caused by moisture movement away from the surface.[47] The CMA mode1[48] developed for NASA provides good results for oven-dry wood, because it includes surface recession but does not take into account moisture desorption. A model of Fredlund[49] includes mass transfer as well as heat transfer and provides for surface recession due to char oxidation. A major problem in the use of the more sophisticated models is the lack of adequate data to use as input.

Most theoretical models for wood charring not only define the charring rate but 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

During the charring of wood caused by fire, the temperature gradient is fairly steep in the wood section remaining uncharred. Some loss of strength undoubtedly results from elevated temperatures. Schaffer *et al*[50] 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 theoretical models discussed previously can be used to determine the temperature gradient within the wood remaining uncharred. In tests of sawn timber, Noren[51] found no significant difference between low-grade and high-grade material. For equal stress ratios, the time to failure in fire established for clear wood can be applied to lumber with knots.

There are basically 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 with different properties.

Empirical a Models

In the standard ASTM E 119 test, structural failure is assumed to occur when the member is no longer capable of supporting its design load, the design load being a fraction of the ultimate load of the original beam. Failure occurs when the cross-sectional area of the member has been reduced by

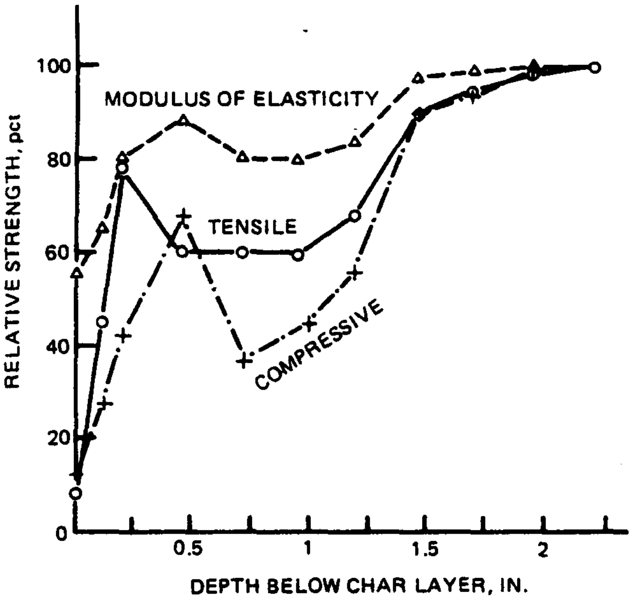

Fig. 4-11.5. Relative modulus of elasticity and compressive and tensile strength as a function of distance below char layer in softwood section under fire exposures. (Expressed in percent of that at 25°C and initial moisture content of 12 percent.) Duration of fire exposure should be equal to or greater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

the charring of the wood. 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 α of their room temperature values.

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

$$\frac{M}{S(t)} = \alpha\sigma_0 \tag{22}$$

where

M = applied moment (design load),
S = section modulus of charred member,
σ_0 = modulus of rupture at room temperature, and
t = time.

Assuming the residual cross-section is rectangular in shape before and during fire exposure, the section modulus of the charred member is[52]

$$S(t) = \frac{1}{6}[(B - 2C_1t)(D - jC_2t)^2] \tag{23}$$

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, and
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 24 through 26:

$$\frac{k}{\alpha}\,\frac{B/D}{[d/D-(1-B/D)]} = \left(\frac{d}{D}\right)^2 \tag{24}$$

for exposure on all four sides,[53] and

$$\frac{k}{\alpha}\,\frac{B/D}{[B/D-2(1-d/D)]} = \left(\frac{d}{D}\right)^2 \tag{25}$$

for exposure on three sides.[54,55]

where

k = load, as fraction of room temperature ultimate load of original member, and
d = critical depth of the uncharred beam.

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

$$t = (D - d)/jC \tag{26}$$

Proposed α values ranged from 0.5 in New Zealand to 0.83 in France.[52] The differences in α values are due to uncertainty, differences in design load, and desired level of safety. In the proposed Eurocode 5, this approach is called the "reduced strength and stiffness method."[28] The reduction factors are a function of the perimeter of the fire-exposed residual cross section divided by the area of the cross section.

The effect of the rounding of the charred member can be taken into account by increasing the value for char rate or including the effect in the empirical α parameter of Equation 22. In addition to bending rupture, the fire resistance of a beam may depend on lateral buckling of the beam.[53,56] Similar expressions can be developed for columns and tension members.[21,52,54,55,57]

The application of the above equations is generally limited to large wood members. Other reviews of fire resistance design methodologies for large wood members include those of Schaffer,[52] Pettersson,[58] and Barthelemy and Kruppa.[59] Kirpichenkov and Romanenkov[60] discussed the calculation procedures in the Soviet Union. The fire resistance of wood structures is also briefly discussed by Odeen.[61]

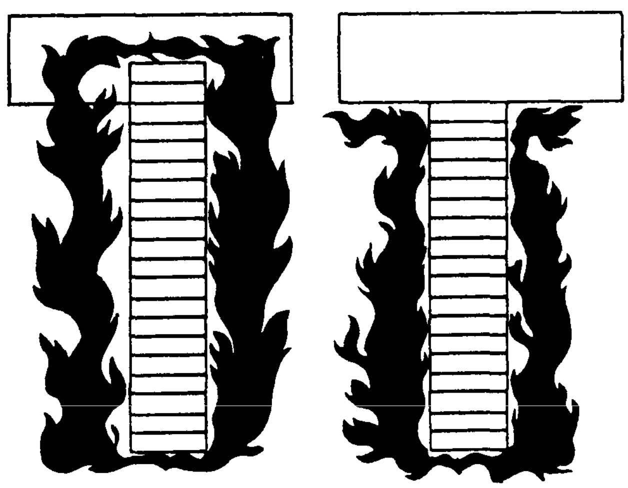

Fig. 4-11.6. Fire exposure of beams on three or four sides.

In developing a model for fire-exposed unprotected wood joist floor assemblies, Woeste and Schaffer[62,63] evaluated various time-dependent geometric terms that could be used to modify the strength reduction factor, α. The selected term was

$$\alpha = \frac{1}{1 + \left(\frac{B + 2D}{BD}\right)\gamma t_f} \qquad (27)$$

where

t_f = failure time, and
γ = empirical thermal degrade parameter.

The model has been experimentally evaluated,[64,65] extended to floor-truss assemblies,[63,67] and used as part of a first-order second-moment reliability analysis of floor assemblies.[62,63] In a model for metal-plate-connected wood trusses,[66] 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.

Composite Models

A second approach to evaluating the fire endurance of a wood member is to assume that the uncharred region consists of layers. 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*[50] analyzed a beam using transformed section analysis. In the similar elastic transformed section model of King and Glowinski,[68] the heated zone of the remaining wood section is divided into two layers at elevated temperatures.

For a second model with layers, an equivalent zero-strength layer, δ, was calculated.[50] For bending, the δ was estimated to be 8 mm (0.3 in. thick). This zero-strength layer, δ, was added to the char depth, βt, to obtain the total zero-strength layer. The rest of the member was then evaluated using room temperature property values. 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.[69] This zero-strength layer approach is called the "effective cross-section method" in Eurocode 5.[28]

For fire-damaged members, Williamson[70] recommended δ 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.

Do and Springer[71-73] have 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[54] 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 22 through 26. These formulas are contained within model building code documents and the *Supplement to the National Building Code of Canada*.[5] The methodology is discussed in two wood industry publications.[74,75] These formulas give the fire resistance time, t, in minutes, of a wood beam or column with minimum nominal dimension of 6 in. The net finish width for a nominal 6-in. glued-laminated member is 5⅛ inches.

For beams, the equations are

$t = 2.54\, ZB\, [4 - 2\, (B/D)\,]$ for fire exposure on four sides (28)

$t = 2.54\, ZB\, [4 - (B/D)\,]$ for fire exposure on three sides (29)

where

B = width (breadth) of a beam before exposure to fire (in.),
D = depth of a beam before exposure to fire (in.), and
Z = load factor. (See Figure 4-11.7.)

For columns, the equations are

$t = 2.54\, ZD\, [3 - (D/B)\,]$ for fire exposure on four sides (30)

$t = 2.54\, ZD\, [3 - (D/2B)\,]$ for fire exposure on three sides (31)

where

B = larger side of a column (in.), and
D = smaller side of a column (in.).

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, (in.). Currently, the codes do not permit the wide side of the column to be the unexposed face (Equation 30). 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 1½ in. of wood, fire-rated gypsum board, or any coating approved for a 1-hr rating. The American Forest &

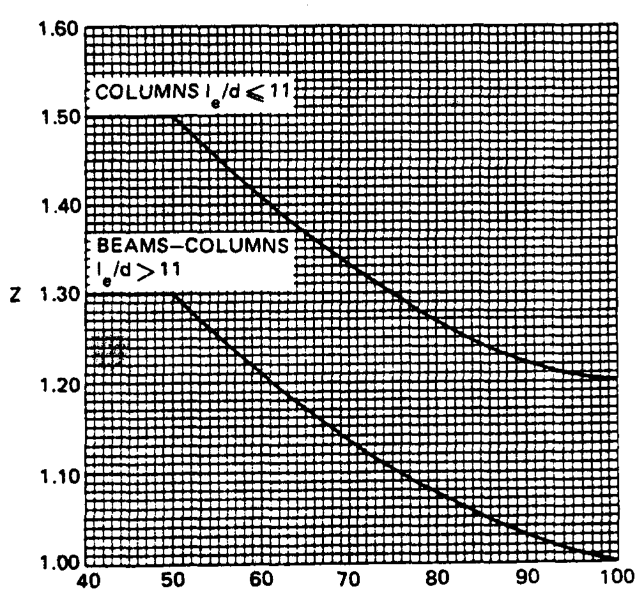

***Fig. 4-11.7.** Load factor versus load on member as percent of allowable. (NBCC uses 12 instead of 11 as criterion for two curves.)*

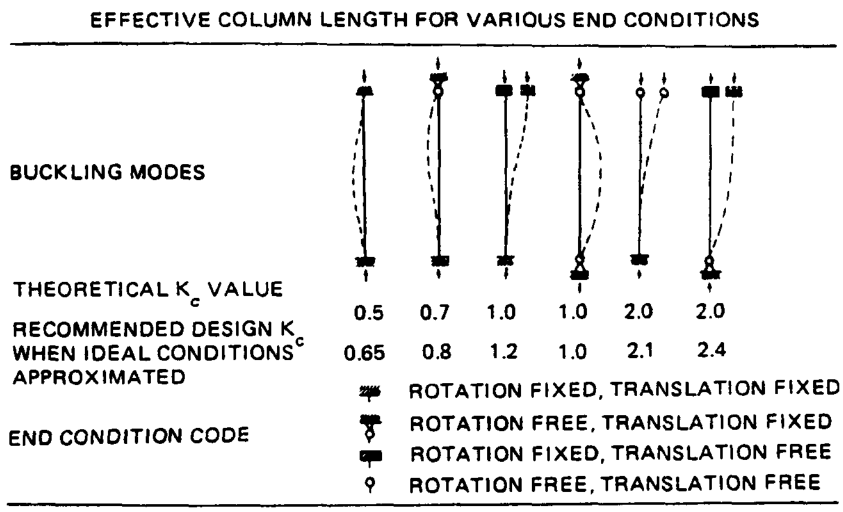

Fig. 4-11.8. Effective column length.

Paper Association publication[74] on the procedure includes diagrams giving typical details of such protection. Carling[76] summarized work done in Europe cm the fire resistance of joint details in load-bearing wood construction. The new Eurocode 5[28] 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 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 5⅛-in. × 21-in. beam exposed to fire on three sides and loaded to 75 percent of its allowable load.

D = 21 in.
B = 5.125 in.

From Figure 4-11.7, Z for a beam loaded to 75 percent of allowable is 1.1. From Equation 29,

$$t = 2.54(1.1)(5.125)[4 - (5.125/21)]$$
$$t = 53.8 \text{ min.}$$

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 *Wood Handbook: Wood as an Engineering Material.*[77] Equations and graphs of the strength and stiffness of wood as functions of temperature and moisture content are available,[78-80] but additional research is needed to better understand these relationships. Thermal properties can also be found in the various references for charring models and in other sources.[81] Thermal properties are needed for char and wood at the higher temperatures.

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.[77] 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.[77] The density of wood relative to the density of water, i.e., specific gravity, is normally used to express the density. The specific gravity of wood 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 hydroscopic 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 a moisture content in excess of 100 percent. However, air-dry wood comes to equilibrium at a moisture content less than 30 percent. Under the conditions stated in ASTM E 119 (23°C, 50 percent relative humidity), wood has an equilibrium moisture content of 9 percent. At 23°C, 65 percent relative humidity, the equilibrium moisture content is 12 percent.[77] 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 for moisture contents below 40 percent[77] is

$$k = S\,(0.00020 + 0.000004\,M) + 0.024$$

where

k = thermal conductivity (W/m °C),
S = density based on volume at current moisture content and oven-dry weight (kg/m^3), and
M = moisture content (percent).

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 2.0 to 2.8 times the transverse property.

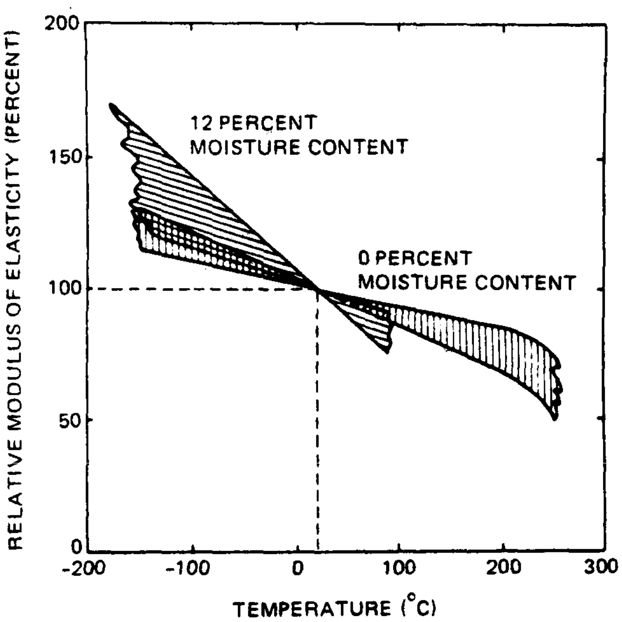

Fig. 4-11.9. The immediate effect of temperature on modulus of elasticity parallel to the grain at two moisture contents relative to value at 20°C. The plot is a composite of results from several studies. Variability in reported trends is illustrated by the width of bands.[77]

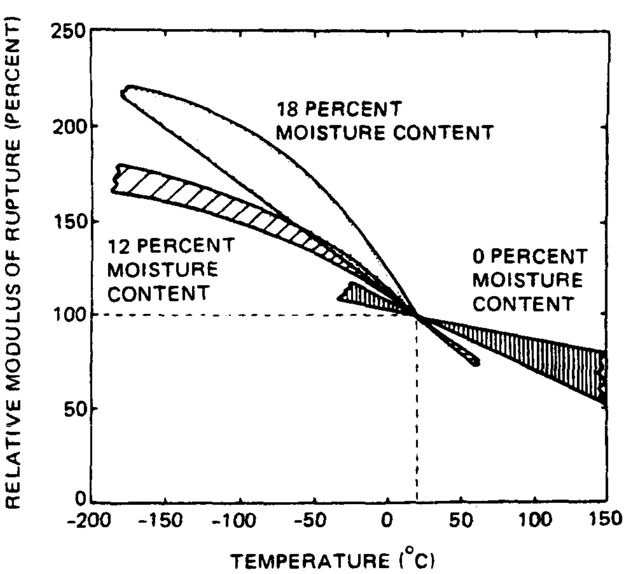

Fig. 4-11.10. The immediate effect of temperature on modulus of rupture in bending at three moisture contents relative to value at 20°C.[77]

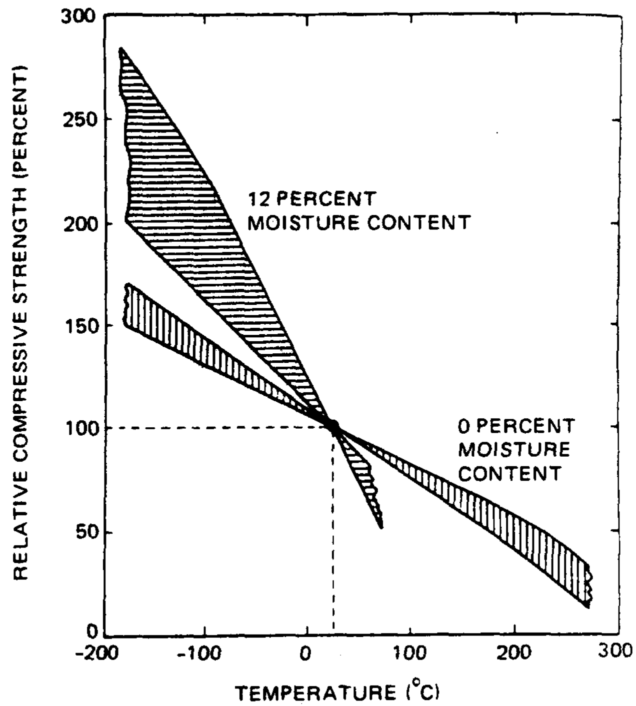

Fig. 4-11.11. The immediate effect of temperature on compressive strength parallel to the grain at two moisture contents relative to the value at 20°C.[77]

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 specific heat capacity (kJ/kg °C) of dry wood is approximately related to temperature, *t,* in °C by[77]

$$\text{Specific heat capacity} = 1.125 + 0.00452\ t$$

The major components of wood are cellulose, lignin, hemicellulose, 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 hemicellulose are different for the hardwood and softwood species. Chemical composition can affect the kinetics of pyroysis (Equation 20) 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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