SECTION 4

13 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 ASTM International (ASTM) Standard E119,[1] International Organization for Standardization (ISO) Standard 834,[2] and similar standards. These ratings are published in listings, such as Underwriters Laboratories *Fire Resistance Directory*,[3] Gypsum Association's *Fire Resistance Design Manual*,[4] American Wood Council's *Design for Code Acceptance* publications,[5] and those in building codes.[6] The ratings listed are limited to the actual assembly tested and normally do not permit modifications such as adding insulation, changing member size, changing interior finish, or increasing the spacing between members. Code interpretation of 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. ASTM Standard E20327 provides guidelines on such extension of fire resistance results obtained from the standard ASTM E119 fire test.

Three procedures for calculating fire resistance ratings have U.S. building code acceptance: the T.T. Lie[8] and the *National Design Specifcation® for Wood Construction* (NDS®)[9] methodologies for calculating fire resistance ratings of exposed wood members and the component additive method (CAM) for protected wood-frame walls, floors, and roofs.[10] The T.T. Lie method is limited to beams and columns. The T.T. Lie methodology and the CAM procedures were developed in Canada and have Canadian code acceptance.[11]

In Europe, the Eurocode 5 (EN 1995-1-2[12] and its corrigendum[13]) on design of timber structures provides calculation methods for the fire design of timber structures. A review of the development of EN 1995-1-2, improvements from the earlier ENV 1995-1-2,[14] and references for the research results used to support its provisions are provided by König[15,16] Two publications on the overall topic of structural fire design are Structural Fire Protection, edited by T.T. Lie,[17] and *Structural Design for Fire Safety*, by Andrew H. Buchanan.[18]

When attention is given to all details, the fire resistance 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

Contribution of the Protective Membrane

Gypsum wallboard and wood paneling are two common types of protective membrane that provides the first line of resistance to 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 10 rules of fire endurance rating.[17,19] These 10 rules (Figure 4-13.1) 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 CAM (discussed in the following subsection).

Component Additive Method

The component additive method (CAM) is a calculation procedure to determine fire resistance ratings of

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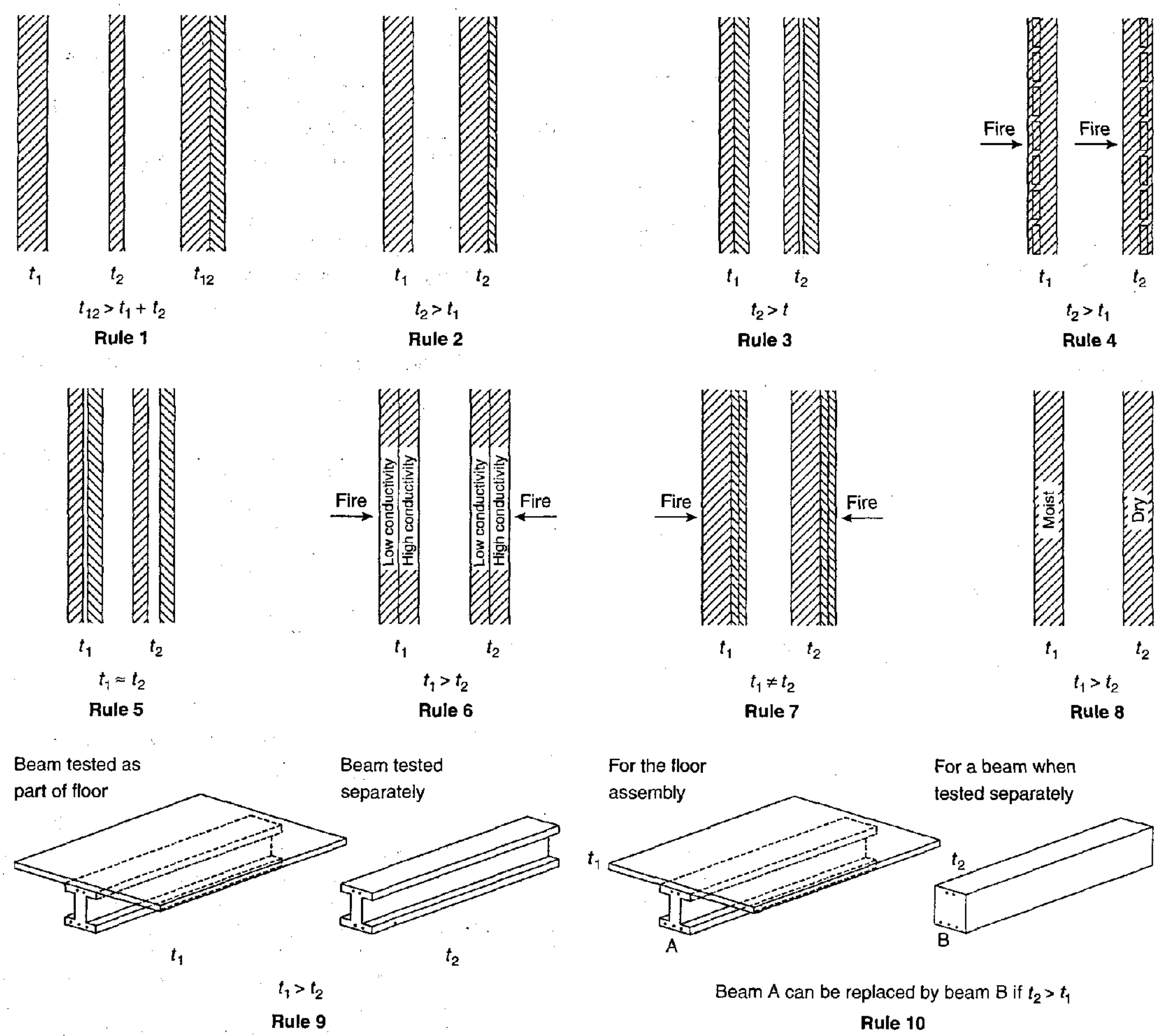

Figure 4-13.1. ***Harmathy's 10 rules of fire endurance.***[19]

light-frame wood floor, roof, and wall assemblies. With this procedure, as with Harmathy's rules 1 and 2, one assumes that a time can be assigned to the type and thickness of the protective membrane 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 plus the time assigned to the framing. CAM was developed by the National Research Council of Canada (NRCC) and has code approval in both the United States and Canada. More recently, Richardson and Batista[20] evaluated the methodology using results from tests of light-frame walls lined with gypsum board.

The times assigned to the protective membranes (Table 4-13.1), the framing (Table 4-13.2), 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 minutes. The times given in Table 4-13.1 are based on the

Table 4-13.1 ***Time Assigned to Protective Membranes****

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

***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 4-13.2 ***Time Assigned for Contribution of Wood Frame****

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

*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.

membrane's ability to remain in place during fire tests. 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.

The type of fasteners and their spacing on the protective membrane can be critical factors in the performance of the membrane in a fire resistance test. Reference should be made to similar tested assemblies. The addition of insulation to a wall assembly can increase its fire resistance.[21] Adding rock wool or slag mineral wool insulation batts for additional protection to the wood stud wall generally has an assigned time of 15 minutes, which is added to the sum of the times for the framing and the protective membrane to obtain the rating for the wall assembly. Assigned times, if any, for glass fiber insulation depend on the codes. The effect of adding insulation to the fire resistance of a floor or roof assembly depends on its location within the assembly and the method of attachment. In the case of floor assemblies, adding insulation can decrease the fire resistance of the assembly.[21]

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 4-13.1 with an assigned time of 15 minutes or greater.

The application of the method in the building codes is generally limited to 60 or 90 minutes. Additional information can be found in publications of the American Forest & Paper Association[10] and the Canadian Wood Council.[11] 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. x 4 in. [51 mm x 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 4-13.1:	
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 4-13.2:	
Wood stud framing	20 min
Calculated rating (total)	60 min

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

There is also a CAM in Eurocode 5 based on work in Sweden.[22,23] In the European CAM, the fire separation function of wall and floor assemblies is calculated as the sum of the contribution to fire resistance from each layer of material:

$$t_{ins} = \sum_i t_{ins,0,i} k_{pos} k_j \tag{1}$$

where

$t_{ins,0i}$ = Basic insulation value of layer i (min)
k_{pos} = Position coefficient of layer i in relation to the fire
k_j = Joint coefficient of layer i

Application of this CAM to address the insulation aspect of fire resistance includes consideration of the different paths for heat transfer through the assembly. Schleifer et al.[24] examined possible modifications to the current Eurocode 5 procedure to consider the impact of the adjacent layers on the position coefficient. The Eurocode 5 also includes design procedures for fire resistance of load-bearing insulated light-frame floors and walls that consider charring of the wood joist or stud. There are separate procedures for wall and floor assemblies with and without cavities filled with rock (mineral wool) or glass fiber insulation.

In New Zealand publications,[25] an approach described as the onset of char method is used to determine the fire ratings of light-frame assemblies. Because 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. As with the onset of char method, 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. Using the results of the recent series of wall tests conducted in Canada, Sultan and Kodur[26] examined the effects of insulation type, insulation width between studs, resilient channel location, gypsum board thickness, number of gypsum board layers, glass fiber in the gypsum board core, gypsum board mass per unit area, and stud type. For load-bearing wood stud walls, the fire resistance is reduced when resilient channels are used to attach the gypsum boards on the fire-exposed side of the studs.[27] Clancy[28] used his model to examine the effects of various variables on the times for structural collapse.

Models for Light-Frame Construction

The protective membrane contributes to fire resistance by providing thermal protection. Numerical heat transfer methodologies are available to evaluate this thermal protection. In most cases, the models were developed for light-frame wall assemblies. A recent extensive literature review of efforts to model the fire resistance of light-frame construction is provided by Bénichou and Sultan.[29] In early work, Fung[30] developed a one-dimensional finite difference model and computer program for thermal analysis of walls. Gammon[31] developed a two-dimensional finite element heat transfer model for wood-stud wall assemblies. WALL2D, developed by Forintek Canada, is a two-dimensional finite-difference model for predicting heat transfer through wood stud walls exposed to fire.[32,33] Difficulties in modeling the charring of wood, and the physical deterioration of the panel products complicate these numerical methodologies. Other research on models for light-frame construction includes activities in Canada,[34,35] Sweden,[36] New Zealand,[37,38] and Australia.[39,40] In addition to modeling heat transfer, these efforts have included the modeling of the structural capacity of the light-frame assemblies. WALL2D has been used with a simple structural model to predict structural collapse .[41]

As part of the development of such models, research has been done on the properties of gypsum board. Cramer et al.[42] examined mass loss and mechanical properties of gypsum board at elevated temperatures. Bénichou and Sultan[43] reported test results for thermal conductivity, specific heat, mass loss, and thermal expansion/contraction for wood, gypsum, and insulation. Craft et al.[44] developed Arrhenius rate constants for the calcinations of the gypsum. Thomas[45] reviewed thermal data for gypsum board and made modifications to obtain apparent values for the properties that were suitable for a heat transfer model.

Direct Protection of Wood Members

The steel industry improves the fire resistance 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 almost nonexistent. The fire-retardant coatings marketed for wood are designed and recognized only for use to reduce the spread of flames over a surface (flame spread).

Depending on 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.[46-48] 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.[49] Bending of the beams during the fire test resulted in adhesion problems. Tests on coated timber members were also reported in Finland and the U.S.S.R.[50]

There are some published data on the protection provided by directly covering a wood member with gypsum board or other nonwood panel products. The charring of wood beneath cladding is addressed in the Eurocode 5 by adjusting the charring rate of the wood for the period before and after the failure of the different types of protective panel products. Gardner and Syme[51] 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. Richardson and Batista[52] tested wood decks with and without gypsum board protection. A 16-mm ($^5/_8$-in.) thick Type X gypsum board increased the times for flame penetration from 4.5 minutes to 44 minutes. In a study of engineered wood rim board products, White[53] investigated the charring rates of wood composite rim boards with and without the protection of one or two layers of gypsum board when subjected to ASTM E119 exposure. Based on tests in a cone calorimeter, Tsantaridis et al.[54] provided information on the charring of wood protected by gypsum board when exposed to 50 kW/m^2.

Fire-Resistive Exposed Wood Members

As the wood member is exposed to fire, charring reduces the cross section of the member. In addition to charring of the member, the residual structural capacity is affected by the elevated temperature gradient within the uncharred wood. The fire-resistive characteristics of exposed wood members are due to the insulative characteristics of the char layer and the sharp temperature gradient beneath the base of the char layer. As a result, even an unprotected structural wood member retains its structural stability in a fire for a period of time. In an engineering analysis of the fire resistance of an exposed wood member, information is needed on charring rate, ratio of ultimate strength to design values, and reduction in strength due to temperature gradient within the uncharred cross section. Using such engineering analyses, Lie[55] developed simple formulas for calculating the fire resistance of large wood beams and columns that require the user to know only the dimensions of the structural element and load as a fraction of the full design load.

T. T. Lie Method

These formulas of T. T. Lie for beams and columns[55] are recognized by building codes in the United States for glued-laminated and solid-sawn timbers[6] and in Canada for glued-laminated timbers. The methodology is discussed in wood industry publications.[8,11,56] 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.) or less. The net finish width for a nominal 152 mm (6 in.) glued-laminated member is 130 mm ($5^1/_8$ in.).

For beams, the equations are

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

$$t = 2.54ZB\left[4 - \left(\frac{B}{D}\right)\right] \quad \text{for fire exposure on three sides} \qquad (3)$$

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 (Figure 4-13.2)

For columns, the equations are

$$t = 2.54ZD\left[3 - \left(\frac{D}{B}\right)\right] \quad \text{for fire exposure on four sides} \qquad (4)$$

$$t = 2.54ZD\left[3 - \left(\frac{D}{2B}\right)\right] \quad \text{for fire exposure on three sides} \qquad (5)$$

where

B = Larger side of a column (in.)

D = Smaller side of a column (in.)

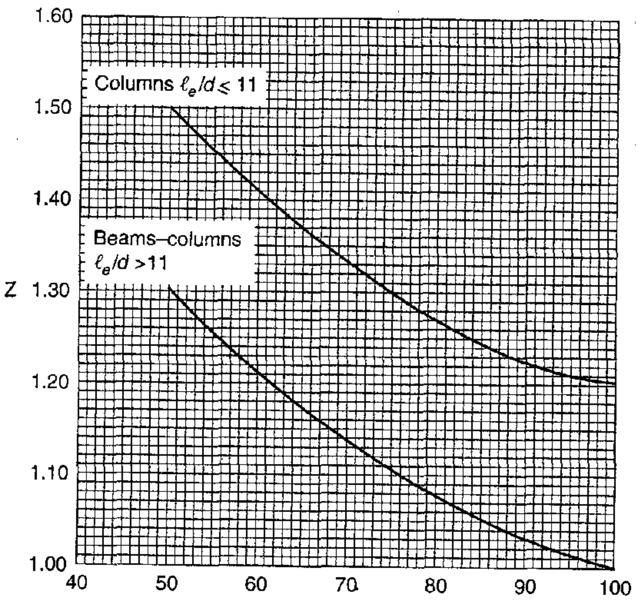

Figure 4-13.2. Load factor versus load on member as percentage of allowable. (Canada uses 12 instead of 11 as criterion for two curves.) Effective column length, ℓ_e, is equal to $K_e \ell$ (Figure 4-13.3) and d is cross-sectional dimension in plane of lateral support.

The 2.54Z factor in the above equations is 0.10Z for SI units of millimeters. For columns the load factor, Z (see Figure 4-13.2), includes the effect of the effective length factor, K_e (Figure 4-13.3), 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 5). The full dimensions of the column are used even if the column is recessed into a wall.

Effective column length for various end conditions

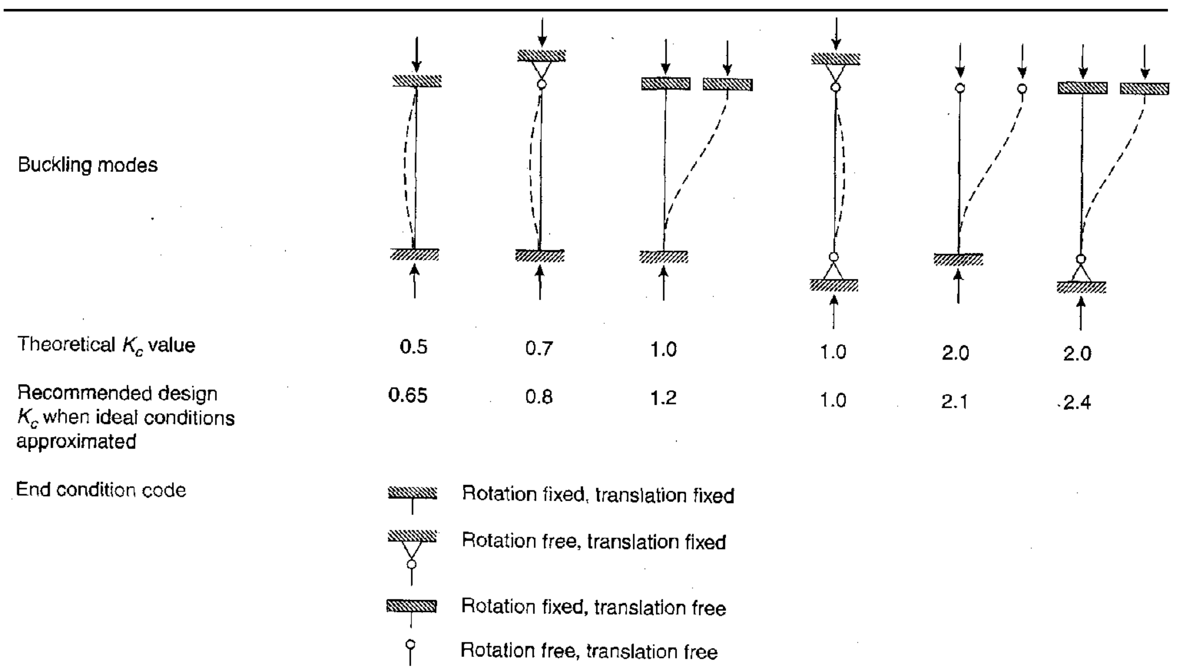

Figure 4-13.3. *Effective column length.*

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-rnm (2-in.) thick outer tension lamination be added to ensure that there is still a high-strength laminate left after fire exposure. Connectors and fasteners are required to be covered by 38-mm (1.5-in.) thick wood or other protective coverings or coating approved for 1 hour rating.[6] Typical details for such connections can be found in industry publications.[8,56]

EXAMPLE 2:

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 4-13.2, Z for beam loaded to 75 percent of allowable is 1.1. From Equation 3,

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

The methodology of this section is applicable only to large wood beams and columns. It also does not allow the user to adjust the charring rate. Other procedures such as the NDS method (discussed later in this chapter) and the various methods described in Eurocode 5 allow the user to specify the applicable charring rate.

Charring of Wood

Wood undergoes thermal degradation (pyrolysis) when exposed to fire (Figure 4-13.4). The thermal degradation process depends on the temperatures and inorganic impurities such as fire-retardant chemicals.[57] The pyrolysis and combustion of wood have been studied extensively. Past literature reviews include publications by Browne,[58] Schaffer,[59,60] Hall et al.,[61] and Hadvig.[62] Most recently, Babrauskas[63] reviewed literature on wood charring and the use of charring rate of wood as a tool for fire investigations. By converting 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.

Charring rate generally refers to the linear rate at which wood is converted to char. Under standard fire exposure, 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. A temperature of 300°C is widely used to define the base of the char layer. Early U.S. research used a temperature of 550°F, and SI conversion to inch-pound units resulted in 288°C,

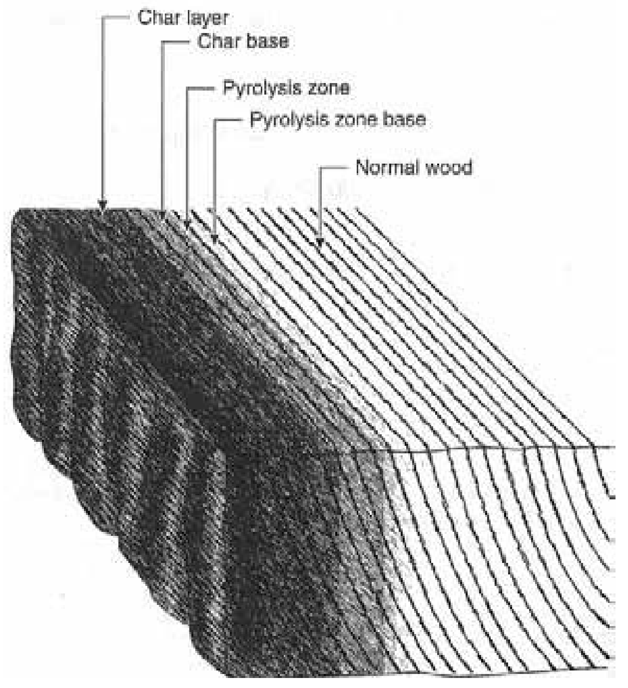

Figure 4-13.4. ***Degradation zones in a wood section.***

290°C, and 300°C being used for 550°F. To determine charring rate, both empirical models based on experimental data and theoretical models based on chemical and physical principles are used.

Standard ASTM E119 Fire Exposure

Expressions for charring rate in the standard ASTM E119 test are the result of many experimental studies. As given in the Eurocode 5, the normal equation for the char depth at a given time is of the form

$$d_{char} = \beta t \qquad (6)$$

where

d_{char} = Design charring depth

β = Design charring rate

t = Time

The design values for charring rate depend on the fire resistance methodology being used. 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. This is for one-dimensional charring in a semi-infinite slab. 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.[61] Schaffer[64] 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 β (mm per min, the reciprocal of charring rate) were

$$\beta = 1/[(0.002269 + 0.00457u)\rho + 0.331] \quad \text{for Douglas-fir} \tag{7}$$

$$\beta = 1/[(0.000461 + 0.00095u)\rho + 1.016] \quad \text{for southern pine} \tag{8}$$

$$\beta = 1/[(0.001583 + 0.00318u)\rho + 0.594] \quad \text{for white oak} \tag{9}$$

where

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

ρ = Density (dry mass, volume at moisture content u)

White65 developed an empirical model based on eight species. The char rate equation was of the form

$$t = mx_c^{1.23} \tag{10}$$

where

t = Time (min)

m = Char rate coefficient

x_c = Char depth (mm)

This nonlinear char model is used in the NDS calculation procedure for exposed wood members. The char rate coefficients ranged from 0.42 to 0.84 mm/min$^{1.23}$ for the eight species.[65,66] Average values for the char rate coefficients were 0.555 for southern pine, 0.554 for western red cedar, 0.598 for redwood, 0.734 for Engelmann spruce, 0.498 for basswood, 0.653 for hard maple, 0.747 for red oak, and 0.607 for yellow poplar. The char rate coefficient was found to be correlated to density, moisture content, and a char contraction factor, which 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). The application of this nonlinear model to composite wood products is discussed by White.[67,68] Other researchers have concluded that there is not a correlation between the char rate and density.[69]

In Eurocode 5, the design charring rate, β_o, in Equation 6 is the rate observed in one-dimensional experiments. The listed design charring rates for timbers include 0.65 mm/min for solid-sawn or glued-laminated softwood timber (characteristic density of 290 kg/m^3 or greater), solid-sawn or glued-laminated hardwood timbers (characteristic density of 290 kg/m^3), and laminated veneer lumber (LVL) (characteristic density of 480 kg/m^3 or greater); and 0.50 mm/min for solid or glued-laminated hardwood with a characteristic density of 450 kg/m^3 or greater. 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 notional design charring rate, β_n, includes 0.7 mm/min for glued-laminated softwood and beech timbers (characteristic density of 290 kg/m^3 or greater), solid-sawn or glued-laminated hardwood except beech timbers (characteristic density of 290 kg/m^3), and LVL (characteristic density of 480 kg/m^3 or greater); 0.8 for solid softwood and beech timber (characteristic density of 290 kg/m^3 or greater); and 0.55 mm/min for solid-sawn or glued-laminated hardwood except beech (characteristic density of 450 kg/m^3 or greater). Except for beech, the charring rates for hardwoods with characteristic densities between 290 and 450 kg/m^3 are linear interpolations of charring rates for 290 and 450 kg/m^3. The concept of notional charring rates in the Eurocode 5 is discussed by König.[70]

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. In tests of solid timber beams, Frangi and Fontana[69] observed an increase in the charring rate when the residual cross section was smaller than 40 to 60 mm. In Eurocode 5, design charring rate listed for panels (20 mm thick and characteristic density of 450 kg/m^3) includes 0.9 mm/min for wood paneling and wood-based panels other than plywood and 1.0 mm/min for plywood. Kanury and Holve[71] suggest the model

$$\frac{\ell}{t} \approx \left(\frac{2}{a}\right)\left(1 - \frac{b\ell}{a}\right) \tag{11}$$

where

ℓ = Thickness of slab (mm)

t = Fire resistance 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[72] provided the equation

$$b_m = 1.128x + 0.0088x^2 \tag{12}$$

where

b_m = Contribution to fire resistance (min)

x = Panel thickness (mm)

The equation is based on data for various wood-based panel products.

The effect of fire-retardant treatment and adhesives on fire resistance depends on the type of adhesive or treatment. The charring rate of wood laminates bonded with phenol adhesives is considered to be consistent with that of solid wood. Tests of a phenol-resorcinol adhesive and a melamine adhesive showed no delamination at the glueline in the wood beneath the char layer.[73] Delamination beneath the base of the char layer occurred at the gluelines for a polyvinyl adhesive.[73] A note in the Eurocode 5 states that the softening temperature is considerably below the charring temperature of the wood for some adhesives. Tests have shown that epoxy-based adhesives can have poor fire performance.[18] As of 2007, there were ongoing research efforts in the United States to develop qualification tests for the performance of adhesives in fire-rated wood assemblies. An initial effort was a new test protocol for evaluating the shear strength of adhesive bonds in laminated wood products at elevated temperatures.[74,75] In Europe, Källander and Lind conducted a comparative study of six different adhesives before and after exposure of glulam beams to fire.[76] Fire-retardant treatments are designed to reduce flame spread. However, a few fire retardants have been found to improve charring resistance.[77]

Nonstandard Fire Exposures

The above equations were stated to apply to the standard ASTM E119 or ISO 834 fire exposure. Data on charring rates for other fire exposures have been limited. Schaffer[64] provided data for constant temperatures of 538°C (1000°F), 815°C (1500°F), and 927°C (1700°F). Lau et al.[78] 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[79] 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.[80-86] 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.[83] 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.[80,81] Charring rate has been found to be proportional to the ratio of external heat flux over density.[83,85] Eurocode 5 includes equations for parametric fire exposures in which the load-bearing function must be maintained during the complete duration of the decay phase or for a specified period of time.

Hadvig's Equations for Nonstandard Fire Exposure

Hadvig[62] has developed equations for nonstandard fire exposure. The charring rate in a real fire depends on the severity of the fire to which the wood is exposed. The fire severity depends on such factors as available combustible material (fire load) and available air supply (design opening factor). The design fire load is

$$q = k \cdot \frac{Q}{A_t} \tag{13}$$

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)

A_t = Total internal area of the compartment, including floor, walls, ceiling, windows, and doors (m^2)

The transfer coefficients are given in Table 4-13.3 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.

Table 4-13.3 ***The Transfer Coefficient, k***[62,87]

Type of Fire Compartment[a]	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/m^3)

E = 50 percent gas concrete (density 500 kg/m^3), 33 percent concrete, and 17 percent 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 1800 kg/m^3)

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/m^3), 10 cm air space, and another double plasterboard (2 x 13 mm) (density 790 kg/m^3)

H = Steel plate on either side of 100 mm mineral wool (density 50 kg/m^3)

[b]The higher values apply to q< 60 MJ/m^2; the lower values apply to q > 500 MJ/m^2. Intervening values are found by interpolation.

The geometrical opening factor is

$$F' = \frac{A\sqrt{h}}{A_t} \tag{14}$$

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)

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

The design opening factor is

$$F = F' \cdot k \cdot f \tag{15}$$

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 4-13.5 and 4-13.6), increases the opening factors when there are horizontal openings. For only vertical openings, f is equal to 1.

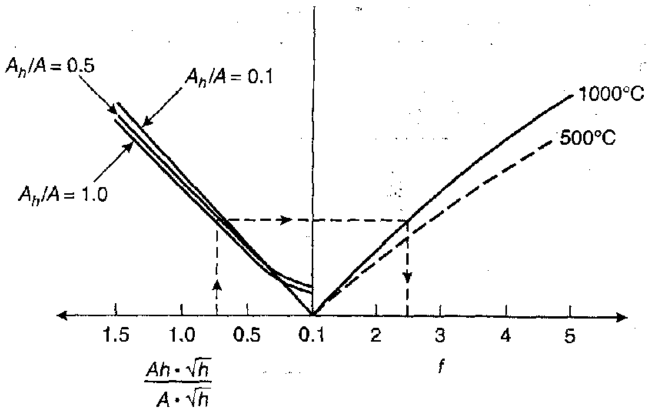

Figure 4-13.5. ***Diagram for the determination off for fire temperatures of 500°C and 1000°C.***[62]

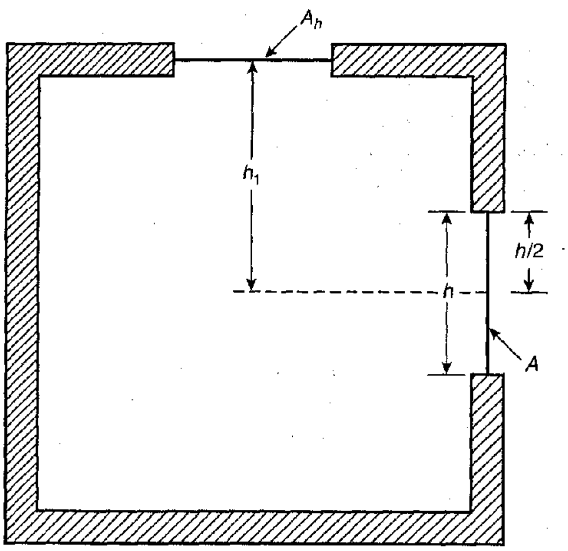

Figure 4-13.6. ***Simplified sketch of vertical cross section of ventilated compartment with notation.***[62]

Hadvig's[62] equations are

$$\theta = 0.0175 \frac{q}{F} \tag{16}$$

$$\beta_0 = 1.25 - \frac{0.035}{F + 0.021} \quad \text{for} \quad 0.02 \tag{17}$$

$$X = \beta_0 \cdot \tau \quad \text{for} \quad 0 \le \tau \le \frac{\theta}{3} \tag{18}$$

$$X = \beta_0 \left(-\frac{1}{12}\theta + \frac{3}{2}\tau - \frac{3}{4}\frac{\tau^2}{\theta} \right) \quad \text{for} \quad \frac{\theta}{3} \le \tau \le \theta \tag{19}$$

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 15)

q = Design fire load (MJ/m^2) (defined in Equation 13)

ρ = Time (min)

These equations are valid for fire exposures less than 120 minutes 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 16 and 17 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 18 is applicable for τ less than θ. Equations 16 through 19 are for glued-laminated 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 mm x 50 mm. Equations 18 and 19 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 18 or 19 by the dimensionless quantity

$$1.35 - 0.0044(b) \tag{20}$$

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

EXAMPLE 3:

The room is a standard fire compartment consisting of brick, concrete, and gas concrete. The floor area is 5 m x 10 m, and the height is 3 m. The openings are one window 1.5 m high and 2.0 m wide, three windows 1.5 m high and 1.0 m wide, and one skylight 1.5 m x 3.0 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 a lower calorific value of 17 MJ/kg, describe the charring of a 38 mm x 250 mm wood beam exposed on three sides after 8 minutes of the fire. The geometrical opening factor (Equation 14) 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 15) is

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

The k is obtained from Table 4-13.3 ($k = 1.0$ for type A, $F' = 0.048$). The f is obtained from Figures 4-13.5 and 4-13.6.

$$\frac{A_1\sqrt{h_1}}{A\sqrt{h}} = \frac{(1.5 \times 3)\sqrt{2}}{7.5\sqrt{1.5}} = \frac{4.5\sqrt{2}}{7.5\sqrt{1.5}} = 0.69$$

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

For $A_h\sqrt{h_h} / A\sqrt{h}$ of 0.69 and A_h/A of 0.6, the f from Figure 4-13.5 is 2.4.

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

The design fire load (Equation 13) 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 θ min (Equation 16):

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

The initial charring rate (Equation 17) will be

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

At 8 minutes, the char depth (Equation 18) 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 18 and 19 are valid. The ratio of the original dimensions is 25/3.8, or 6.6. Because 38 mm is less than 80 mm, the multiplying factor (Equation 20) is

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

At 8 minutes, 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 minutes, 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.

Using an opening factor method and parametric time-temperature curves, equations for natural fires are provided in Eurocode 5. The approach is a simplification of Hadvig's equations. In the 1994 edition[14] of the Eurocode 5, the equation for the parametric charring rate during the period τ_0 is

$$\beta_{par} = 1.5\beta_0 \frac{5F - 0.04}{4F + 0.08} \tag{21}$$

where

$F = F'$ of Equation 14

β_0 = Design charring rate of Eurocode 5

The time period τ_0 is

$$\tau_0 = 0.006 \frac{q}{F} \tag{22}$$

where q is the total design load of Equation 13.

At τ_0, the char rate decreases to zero at $3\tau_0$. The maximum charring depth during the fire exposure and the subsequent cooling period is $2\beta_0\tau_0$. Equations are valid for F between 0.02 and 0.30 $m^{1/2}$, τ_0 of 40 minutes or less, and char depths less than one-quarter of the dimensions. Buchanan[18] provides a table of char rate, char time, and char depth results from the above equations for a range of opening factors. The equations in the 1994 edition[14] were modified for the 2004 edition[12] of the Eurocode 5. In the 2004 equations, the $5F$ and $4F$ in Equation 21 were modified to be a function of the thermal properties of the compartment boundaries. Oleson and König[88] tested glued-laminated beams and found agreement with Hadvig's equations for the wide vertical side of a member. Oleson and König[88] noted that, compared with 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, and work in this area is continuing. Janssens[89] observes that more than 50 wood pyrolysis models have been developed since World War II. Moghtaderi[90] provides a review of pyrolysis models of wood developed over the past 60 years. Theoretical models allow calculation of the charring rate for geometries other than a semi-infinite slab and for nonstandard fire exposures. Robert[91] reviewed 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.[92] The basic differential equation used by Bamford was

$$c\rho \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial X^2} - q \frac{\partial w}{\partial t} \tag{23}$$

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

ρ = Density

In Equation 23, 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 right 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 23, 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[93] added a convection term to Bamford's equation to obtain

$$\rho c \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial X^2} + M c_g \frac{\partial T}{\partial t} - q \frac{\partial w}{\partial t} \qquad (24)$$

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[94] and later revised by Tamanini.[95] Atreya[96] has further revised this model to include moisture absorption. His energy conservation equation is

$$(\rho_a C_{pa} + \rho_c C_{pc} + \rho_m C_{pm}) \frac{\partial T}{\partial t} = \frac{\partial}{\partial X}\left(K \frac{\partial T}{\partial X}\right) + i\left(1 - j\frac{\rho_c}{\rho_f}\right) \cdot$$
$$M_g \frac{\partial H_g}{\partial X} - \frac{\partial \rho_s}{\partial t}\left[-Q + \left(H_a - H_c \frac{\rho_f}{\rho_w}\right) \Big/ \left(1 - \frac{\rho_s}{\rho_w}\right) - H_g\right]$$
$$- \frac{\partial \rho_m}{\partial t}(-Q_m + H_m - H_g) \qquad (25)$$

where

C_p = Specific heat (J/[kgK])

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_x)

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 25 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

$$\frac{\partial M_g}{\partial X} = \frac{\partial \rho_s}{\partial t} + \frac{\partial \rho_m}{\partial t} \qquad (26)$$

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

$$\frac{\partial \rho_s}{\partial t} = -A \frac{(\rho_s - \rho_f)}{(1 - \rho_f / \rho_w)} \exp(-E / RT) \qquad (27)$$

where

A = Frequency factor (1/s)

E = Activation energy (J/mole)

R = Gas constant

Atreya[96] uses a moisture desorption kinetics equation for vaporization of the water in the wood, which is

$$\frac{\partial \rho_m}{\partial t} = -A_m \rho_m \exp(-E_m / RT) \qquad (28)$$

The CMA mode197 developed for NASA provides good results for oven-dry wood because it includes surface recession. Parker[98,99] 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.[100] A model of Fredlund[101] includes mass transfer as well as heat transfer and provides for surface recession due to char oxidation. In a model for wood combustion, Bryden[102] 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. To describe the natural smoldering of logs after a forest fire, Costa and Sandberg[103] modeled the steady one-dimensional propagation of infinitesimally thin fronts of drying, pyrolysis, and char oxidation. Kanury and Holve[71] have presented dimensional, phenomenological, approximate analytical, and exact numerical solutions for wood charring. Other models include those of Havens,[104] Knudson and Schniewind,[105] Kansa et al.[106] Hadvig and Paulsen,[107] Tinney,[108] and Janssens.[89] Badders et al.[109] examined the ability of four commercial finite element analysis programs (FIRES-T3, SAFIR, TASEF, COMSOL) to model exposed wood beams.

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.[110,111] Although primarily for zone models, there is an ASTM *Standard Guide for Data for Fire Models.*[112] 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 al.[113] 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 (Figure 4-13.7).

Various equations for the temperature gradient within the charred wood slab have been developed.[69,114,115] An equation based on a power term is

$$T = T_i + (300 - T_i)\left(1 - \frac{x}{d}\right)^2 \qquad (29)$$

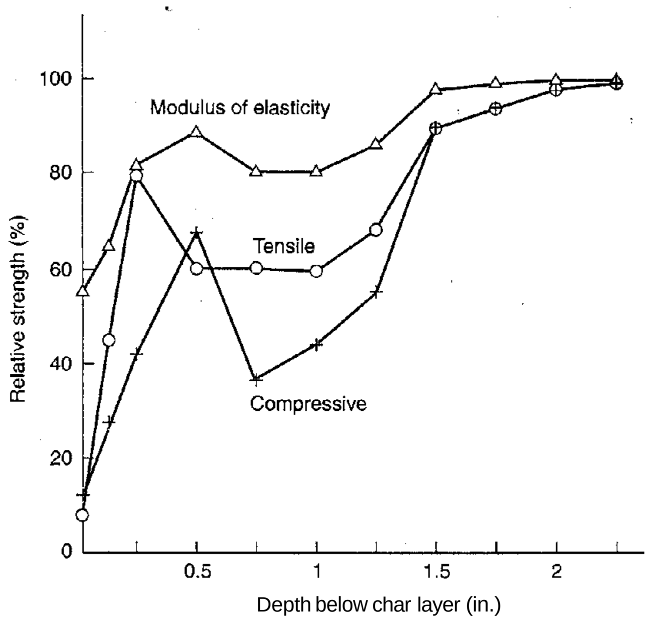

Figure 4-13.7. ***Relative modulus of elasticity and compressive and tensile strength as a function of distance below char layer in softwood section under fire exposures. (Expressed in percentage of that at 25°C and initial moisture content of 12 percent.) Duration of fire exposure should be equal to or greater than 20 minutes to apply results of this figure.***

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,[65] an average value for the thermal penetration depth was 33 mm.[115] Based on European tests, a more conservative value of 40 mm was recommended for the thermal penetration depth.[115] 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.[81] Frangi and Fontana[69] observed that the thermal penetration depth was dependent on time and developed an alternative equation:

$$T(x) = 20 + 180\left(\frac{\beta t}{x}\right)^{\alpha} \qquad (30)$$

where

T = Temperature at depth x (°C)

β = Charring rate (mm/min)

t = Time (min)

x = Distance from the surface of the cross section (mm)

and

$$\alpha(t) = 0.025t + 1.75 \qquad (31)$$

Equation 30 was derived assuming the char front at 200°C and char rate of 0.7 mm/min. Frangi and Fontana[69] also developed the following equation for a timber beam exposed to fire on three sides:

$$T(x,y) = 20 + 180(\beta t)^{\alpha}\left[\left(\frac{1}{x}\right)^{\alpha} + \left(\frac{1}{b-x}\right)^{\alpha} + \left(\frac{1}{y}\right)^{\alpha}\right] \quad (32)$$

where T, t, α, and β are as defined for Equation 30, and x and y are the depths from the surfaces of the cross section in millimeters.

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.

Reduced Properties Models

One 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

$$\frac{M}{S(t)} = \alpha\sigma_0 \quad (33)$$

where

M = Applied moment (design load)

S = Section modulus of charred member

σ_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[114]

$$S(t) = \frac{1}{6}[(B - 2C_1 t)(D - jC_2 t)^2] \quad (34)$$

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 4-13.8)

Alternative to Equations 26 and 27 are the following, Equations 35 through 37:

$$\frac{k}{\alpha}\frac{B/D}{[d/D - (1 - B/D)])} = \left(\frac{d}{D}\right)^2 \quad (35)$$

for exposure on all four sides,[116] and

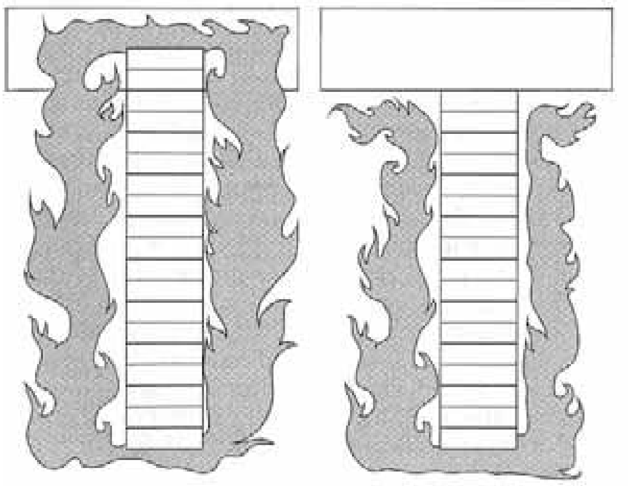

Figure 4-13.8. ***Fire exposure of beams on three or four sides.***

$$\frac{k}{\alpha}\frac{B/D}{[B/D - 2(1 - d/D)]} = \left(\frac{d}{D}\right)^2 \quad (36)$$

for exposure on three sides,[55,117]

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

$$t = (D - d)/jC \quad (37)$$

Proposed a values ranged from 0.5 in New Zealand to 0.83 in France.[114] The differences in α 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, α values would be substantially lower.[118] In Eurocode 5, this approach is called the "reduced properties 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.[116] Similar expressions can be developed for columns and tension members.[55,114,117,119] Reviews of fire resistance design methodologies for large wood members include those of Schaffer,[114] Pettersson,[120] and Barthelemy and Kruppa.[121] Kirpichenkov and Romanenkov[122] discussed the calculation procedures in the Soviet Union. The fire resistance of wood structures is also briefly discussed by Odeen.[123] In developing a model for fire-exposed unprotected wood joist floor assemblies, Woeste and Schaffer[124,125] evaluated various time-dependent geometric terms that could be used to modify the strength reduction factor. The selected term was

$$\alpha = \frac{1}{1 + (B + 2D/BD)\gamma t_f} \quad (38)$$

where

t_f = Failure time

γ = Empirical thermal degrade parameter

The model has been experimentally evaluated,[126,127] extended to floor-truss assemblies,[125,128] and used as part of a first-order second-moment reliability analysis of floor assemblies.[124,125] Reliability-based design of the fire resistance of light-frame construction is also discussed by Lau and Barrett.[118] In a model for metal plate-connected wood trusses,[129] 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.

The models for load-bearing floor joist and wall studs in Annex C of Eurocode 5 incorporate the notional char depth within the calculation of the modification factor for the strength properties. König and Kallsner[130,131] developed such a modification factor for wood I-joists.

Reduced Cross-Section Area Models

A more common approach is to assume an equivalent zero-strength layer, δ, and then evaluate the rest of the member using room-temperature property values. In the model of Schaffer et al.[113] for beams, 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. 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.[132] This zero-strength layer approach is called the "reduced cross-section method" in Eurocode 5. In Eurocode 5, δ is a linear fraction of 7 mm for the initial 20 minutes and 7 mm after 20 minutes. In the NDS method,[9,133,134] 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. Design or characteristic strength values are used in the Eurocode 5 calculations. In Eurocode 5, the design value of strength is the 20th percentile of the cold strength divided by a partial factor equal to one. The design stress to member strength adjustment factors in the NDS are discussd in the next section on the NDS method. 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[135] recommended 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.

NDS Method for Exposed Wood Members

The *National Design Specification for Wood Construction* (NDS®)[9] method for the fire design of exposed wood members is a mechanics-based design method that is applicable to all wood structural members covered under the NDS. With explicit equations for the residual fire resistance of the wood members, it is possible to adjust the equations for other member types and loading conditions. The charring rate can be modified for specific wood products. It is described in chapter 16 of the NDS[9] and other articles.[134] Full documentation is provided in Technical Report 10[133] of the American Forest & Paper Association. In the United States, its code recognition is via the adoption of the 2001 or later editions of the NDS. It is limited to ratings of 2 hours or less.

This effective cross-section method uses the nonlinear charring model of Equation 10 and strength values at ambient temperatures. An increased char rate accounts for reduced strength and stiffness properties and accelerated charring at the corners. The increase in char depth is 20 percent over a nominal char rate that is based on 1 hour of fire exposure. Thus, the effective char rate is given by

$$\beta_{eff} = \frac{1.2\beta_n}{t^{0.187}} \tag{39}$$

where

β_{eff} = Effective char rate (mm or in. per hour) adjusted for exposure time, t

β_n = Nominal char rate (mm or in. per hour) linear char rate based on 1-hour exposure

t = Exposure time

A nominal char rate, β_n, of 38 mm (1.5 in.) per hour is normally assumed for solid-sawn and glued-laminated softwood members. The effective char depth is β_{eff} multiplied by time. Thus, the effective char depth at l hour is 46 mm (1.8 in.) and the equivalent zero-strength layer thickness is 7.6 mm (0.3 in.). The section properties of the members are reduced by the effective char depth for the surfaces that are exposed to the standard fire exposure. The resisting strength or average ultimate residual strength properties are calculated by multiplying the allowable design stress values in the NDS by design stress to member strength adjustment factors. Values for this adjustment factor are 2.85 for bending and tensile strength, 2.58 for compression strength, and 2.03 for beam-buckling and column-buckling strength. As appropriate, the allowable design stress values are also multiplied by a size factor, volume factor, flat use factor, beam stability factor, and column stability factor as described in the NDS. For a fire resistance rating of time *t*, the induced stress of the reduced section of the charred member at time *t* shall not exceed the resisting strength of the member. For glued-laminated timber bending members with tension laminations, the NDS has requirements for the substitution of core laminations with tension laminations. The specifics depend on the fire resistance rating and the details of the beam construction.

Decks

The NDS method addresses the structural requirements for fire resistance of timber decks. Decks are specified to have a thickness of at least 51 mm (2 in.). Butt-jointed decking is designed as a series of beams that have reduced charring on the partially protected sides and normal charring on the exposed bottom surface. The char rate for the sides is one-third of the effective char rate (Equation 39). Single and double tongue-and-groove (T&G) decking is assumed to have charring on only the one bottom face. Janssens[136] applied a transformed section analysis of a timber deck and the Eurocode 5 effective cross-section method to develop a simplified design equation (thickness and load factor as variables) for timber decks that was similar to the T.T. Lie equations.

In addition to the requirement of structural stability, the fire resistance rating of a timber deck also depends on requirements for thermal protection. Thermal protection criteria provide for excessive temperature rise on the unexposed surface and flame penetration. In the United States, there is no recognized procedure for solid wood floors or roofs that include the thermal failure criteria of ASTM E119. The equations for the temperature profile in a wood slab discussed previously can be used to estimate the required thickness to prevent excessive temperature rise.[136,137] A deck is likely to have joints and gaps between the boards that become the controlling factor in the fire resistance of the deck. Joints can be a critical factor in the fire resistance of a wood barrier. Eurocode 5 provides some guidance for joints in wood-based panel products. The estimated failure times for such panel products with a butt joint, lap joint, single T&G joint, or double T&G joint are 20, 30, 40, and 60 percent, respectively, of the failure times for a solid wood barrier calculated using charring rates for wood. The application of these adjustments developed for panel products to gaps in decks has been investigated. Based on a series of tests of timber decks, Richardson and Batista[138] concluded that the failure times for simple butt joints, single T&G joints, and double T&G boards were 10, 40, and 40 percent, respectively, of the times for a solid wood member estimated using charring rates for wood. In the tests, the specification for the gaps between boards was 2 mm (0.08 in.) or less. These tests also illustrated the effect of increasing the thickness of gaps, particularly with butt joints. For gaps of $\leq$1 mm ($\leq$0.04 in.), the tests suggested that failure times for simple butt joints were 30 percent of those for solid-sawn lumber instead of the 10 percent for gaps of 2 mm (0.08 in.) or less.

Adding wood flooring or panel products on top of the timber deck improved the failure times in the tests of Richardson and Batista[138] Paneling on top of the decks provided the most benefits to the fire resistance of decks when the butt joints had 4 mm (0.16 in.) gaps, compared with decks of T&G joints or narrow gaps. Given the limited ability to control gaps between deck boards over time, the best method to address the joint issue is to provide a multilayer deck assembly by adding panel products or other floor topping, such as gypsum concrete or lightweight or normal concrete toppings, on top of the heavy timber decks. Frangi and Fantana[69] found that the fissures between nailed-laminated timber planks did not increase the char rate but noted that the nonexposed surface must be sealed airtight to obtain such results.

Connections

Connectors and fasteners relating to support of the member must be protected for equivalent fire-resistive construction. Carling[139] summarizes work done in Europe on the fire resistance of joint details in load-bearing wood construction. Buchanan[18] also reviews the literature on the fire performance of connections. Eurocode 5 provides rules for the fire resistance of connections and protecting connections in fire-rated timber members, and the subject is discussed by König.[15,16,140] Rules are given for connections made with nails, bolts, dowels, screws, split-ring connectors, shear-plate connectors, and toothed-plate connectors. In U.S. procedures with building code recognition, the protection of connections is addressed by prescriptive requirements. Where minimal 1 hour fire resistance is required, connectors and fasteners must be protected from fire exposure by 38 mm (1½ in.) of wood or other approved covering or coating for a 1 hour rating.[6] Industry publications[8,56] on the T.T. Lie procedure include diagrams giving typical details of such protection.

Composite Models

The most complex approach to evaluating the fire resistance 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 "advanced 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.[113] analyzed a beam using transformed section analysis. In the similar elastic transformed section model of King and Glowinski,[141] 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[142] and by Janssens.[136] A finite difference model for wood beams and columns was developed by Tavakkol-Khah and Klingsch.[143]

Do and Springer[144-146] 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 an oven. Examples of models that use a grid of elements to analyze the residual load capacity of the structural member include ones for wood joists,[147] compression members,[148] and wood studs.[39]

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. General property data for clear wood can be found in various chapters of *Wood Handbook: Wood as an Engineering Material*[66] (available at http://www.fpl.fs.fed.us), which also includes a chapter on fire safety.

Reviews of available data on properties needed to model thermal degradation, charring, and residual load capacity of wood members can be found in the literature.[18,111] Equations and graphs of the strength and stiffness of wood as functions of temperature and moisture content are available.[149-151] Recent research in the development of fire resistance 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.[152] Recent efforts have been on the compression properties of wood.[153,154] The strength reductions given in Eurocode 5 include the time-dependent effects of creep, moisture, and mechanosorption. Such effects are among the reasons for differences reported in the literature. Preheating samples in an oven is not the same as exposing samples to simultaneous thermal and structural loads. Other methodology differences, such as rate of loading, affect the experimental results reported.

Thermal properties can also be found in the various references for charring models and Annex B of Eurocode 5 (EN 1995-1-2). As discussed by König,[155] the thermal properties of EN 1995-1-2 and other sources are often effective property values that are dependent on the assumptions of the model and the experiments used to calibrate the input data. Due to the complexity of wood thermal degradation and the heat and mass transfer within the wood element, some aspects of the complexity are accommodated by adjusting the thermal property data. Thus, such thermal property data may be applicable only to the standard fire exposure used in their development and can produce erroneous results when applied to natural fires and parametric fire curves.[155] This is particularly the case for the thermal properties of the char layer. As discussed by Hadvig,[62] the "char" of the char layer is complex and its thermal characteristics are not the same as those of charcoal.

Although assuming constant property values is often less complicated, 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. Because 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.[63] The density of wood relative to the densify of water (i.e., specific gravity) is normally based on oven-dry weight and volume at some specified moisture content, but in some cases the oven-dry volume is used. As the empirical equations for charring rate show, materials with higher density have slower char rate.

Wood is a hygroscopic material, which gains or loses moisture depending on 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 sufuration point.* At higher moisture contents, water exists in the cell lumens. Many physical and mechanical properties of wood change with moisture content only at moisture contents below the fiber saturation point. Under the conditions stated in ASTM E119 (50 percent relative humidity), the equilibrium moisture content is about 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[66]

$$k = S(0.0001941 + 0.000004064M) + 0.01864 \qquad (40)$$

where

k = Thermal conductivity (W/mK)

S = Density based on volume at current moisture content and oven-dry weight (kg/m^3)

M = Moisture content (percent)

Equation 40 is valid for moisture contents of 25 percent or less, densities greater than 300 kg/m^3, and temperature of 24°C. Conductivity increases about 2 to 3 percent per 10°C.[66]

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 4-13.9 through 4-13.11. Using data from a variety of sources, Buchanan[18] also provides graphs of the temperature effect on mechanical properties. The heat capacity, c_r (kJ/kg K), of dry wood is approximately related to temperature, T (in K), by[66]

$$c_p = 0.1031 + 0.003867T \qquad (41)$$

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.[66]

The major components of wood are cellulose, lignin, hemicelluloses, extractives, and inorganic materials (ash). Softwoods have lignin contents of 23 to 33 percent, whereas 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

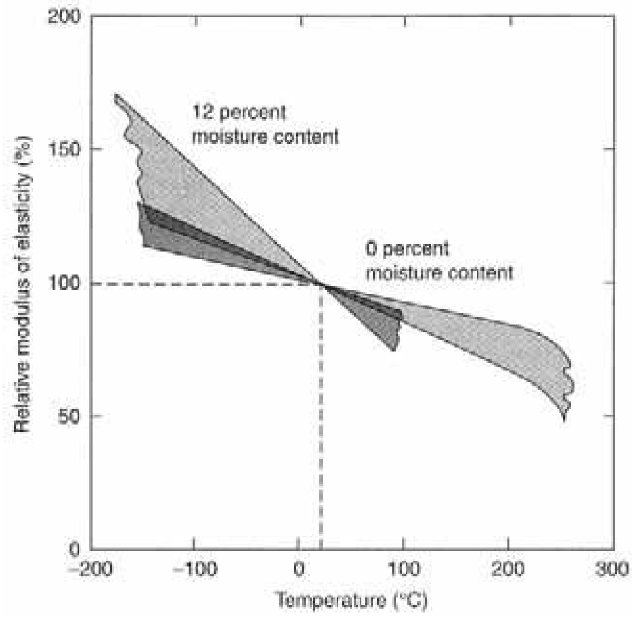

Figure 4-13.9. ***The immediate effect of temperature on modulus of elasticity parallel to the grain at two moisture contents relative to value at 20°C. The plot is a composite of results from several studies. Variability in reported trends is illustrated by the width of bands.*** [66]

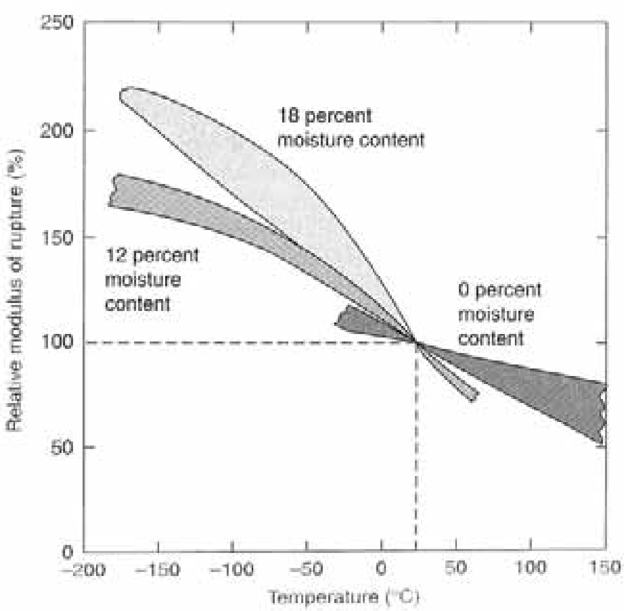

Figure 4-13.10. ***The immediate effect of temperature on modulus of rupture in bending at three moisture contents relative to value at 2O°C.*** [66]

can affect the kinetics of pyrolysis (Equation 27) and the percentage weight of the residual char. In the degradation of wood, higher lignin content results in greater char yield.

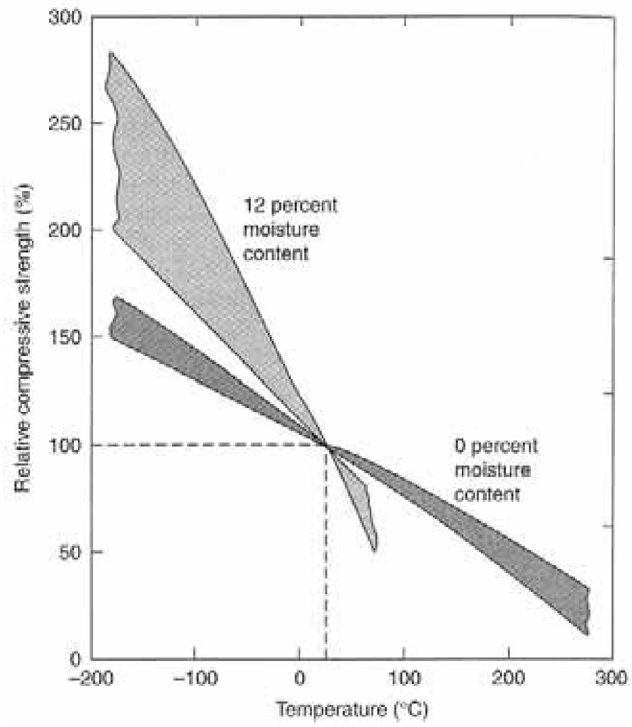

Figure 4-13.11. ***The immediate effect of temperature on compressive strength parallel to the grain at two moisture contents relative to the value at 2O°C.*** [66]

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