The times assigned to protective wall and ceiling coverings are given in Table 5.2. These times are based on the ability of the membrane to remain in place during fire tests. This "assigned time" should not be confused with the "finish" rating of the membrane. A "finish rating" is the time it takes for the temperature to rise 250°F on the unexposed surface of a material, when the material is exposed to a heat source following the ASTM E 119 fire curve. As shown in Table 5.2 some combinations of membranes have been tested, resulting in greater fire endurance times than the sum of the ratings of the individual membranes.

TABLE 5.3

TIME ASSIGNED TO WOOD-FRAME COMPONENTS

Description of Frames	Time (min)
Wood studs, 16 inches on center	20
Wood joists, 16 inches on center	10
Wood roof and floor truss assemblies, 24 inches on center	5

The times assigned to wood studs and joists were determined based upon the time it takes for the framing members to fail after failure of the protective membrane. The fire endurance time assigned to framing members is given in Table 5.3. These times are based on the ability of framing members to provide structural support when subjected to the ASTM E 119 fire endurance test without benefit of a protective membrane. These time values are in part the result of full-scale tests of unprotected wood studs and floor joists, where the structural elements were loaded to design capacity. They apply to all framing members and do not increase if, for example, 2 by 6 inch studs are used rather than 2 by 4 inch studs.

Exposed Plywood: For a wall or partition where only plywood is used as the membrane on the side assumed to be exposed to the fire, insulation should used within the assembly.

TABLE 5.4

TIME ASSIGNED FOR INSULATION OF CAVITY	
Description of Insulation	Time (min)
Add to the fire endurance rating of wood stud walls if the spaces between the studs are filled with rockwool or slag mineral wool batt weighing not less than ¼ lb./sq. ft. of wall surface.	15
Add to the fire endurance rating of non-load bearing wood stud walls if the spaces between the studs are filled with glass fiber batt weighing not less than ¼ lb./sq. ft. of wall surface.	5

Additional fire endurance can be provided to wall assemblies by the use of high density rockwool or paper or foil-faced glass fiber insulation batt. The time assigned to each type of insulation as contributing additional fire endurance to the assembly is presented in Table 5.4.

Unsymmetrical wall assemblies: When dissimilar membranes are used on opposite faces of a wall assembly, the fire endurance shall be determined based on the calculations for the least fire resistant side. Where exterior walls are required to be rated for exposure to fire from the inside only, the non-fire side membrane is permitted to be constructed of any combination of materials listed in Table 5.5.

TABLE 5.5

MEMBRANE ON EXTERIOR FACE OF WALLS		
Sheathing	Paper	Exterior Finish
5/8 inch T&G lumber 5/16 inch exterior grade plywood 1/2 inch gypsum board	Sheathing paper	Lumber siding; or Wood shingles and shakes; or ¼ inch ext. grade plywood; or ¼ inch hardboard; Metal siding; Stucco on metal lath; or Masonry veneer
None	None	⅜ inch ext. grade plywood

Floor/ceiling and roof/ceiling assemblies: Fire resistant floor/ceiling and roof/ceiling assemblies shall have an upper membrane provided in accordance with Table 5.6. Alternatively, any combination of membranes from Table 5.2 with a fire endurance contribution of at least 15 minutes, is permitted to be used on the unexposed (upper) side. Where permitted by the building code, the unexposed membrane may be eliminated.

TABLE 5.6

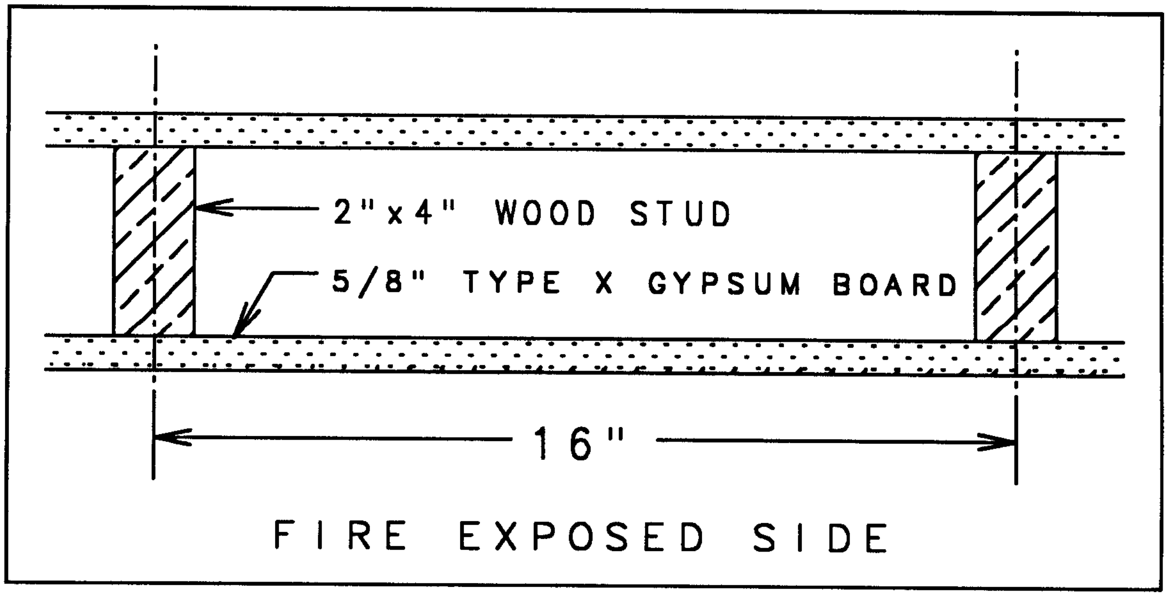
FLOORING OR ROOFING MEMBRANE			
Assembly	**Structural members**	**Subfloor or roof deck**	**Finish flooring or roofing**
Floor	Wood	1/2 inch plywood or 11/16 inch T&G softwood lumber	Hardwood or softwood flooring on building paper; or Resilient flooring, parquet floor, felled-synthetic-fiber floor coverings, carpeting, or ceramic tile on 3/8 in. thick panel-type underlay; or Ceramic tile on 1-1/4 in. mortar bed.
Roof	Wood	1/2 inch plywood or 11/16 inch T&G softwood lumber	Finish roofing material with or without insulation.

EXAMPLE #1

Determine the fire endurance rating of a wall assembly (shown below) having one layer of 5/8 inch Type X gypsum board attached to wood studs on the fire exposed side.

Table 5.2 shows that 5/8 inch Type X gypsum board has a fire endurance time of 40 minutes. Table 5.3 shows that wood studs spaced 16 inches on center have a fire endurance time of 20 minutes. Summing the two components results in a fire endurance rating of 60 minutes.

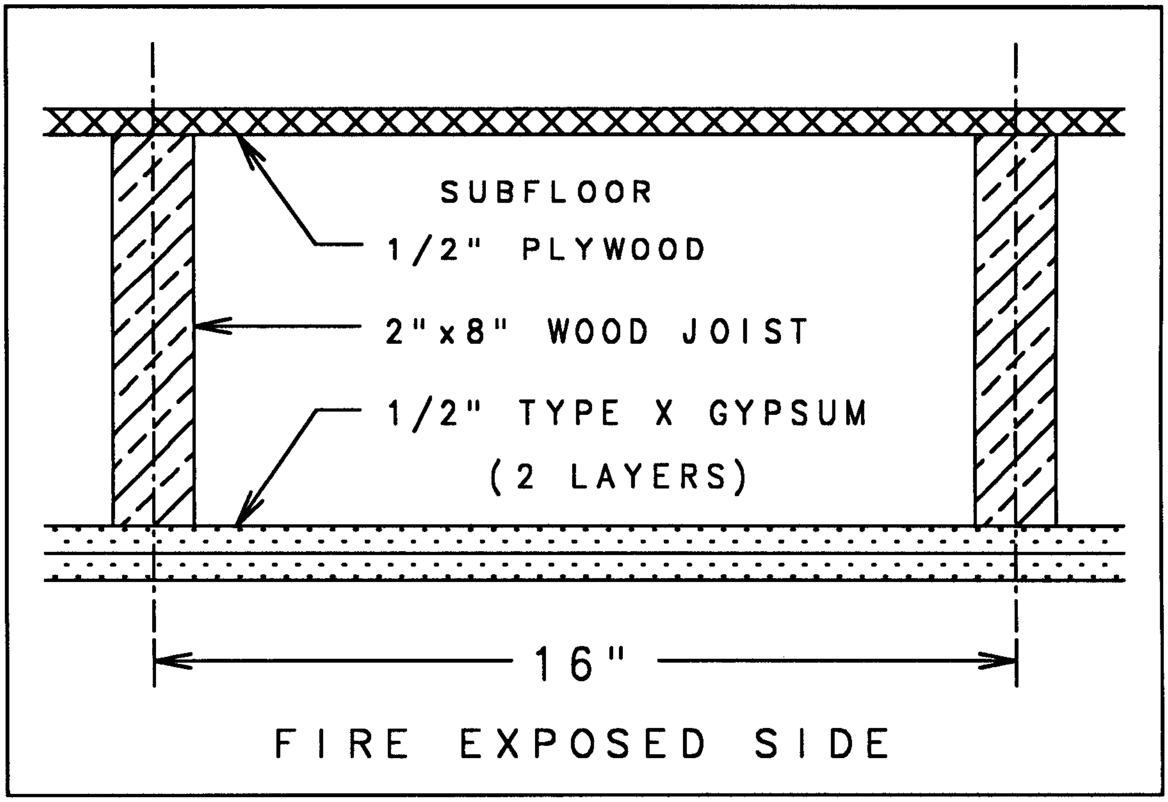
If the wall is assumed to be exposed to fire from both sides (e.g. for interior fire rated walls, each surface of the framing member would be required to be fire protected with at least 40 minutes of membrane coverings in Table 5.2. If the proposed wall is assumed to be exposed to fire from one side only, as is required for an exterior wall, the fire exposure is assumed to be from the interior, which would require a total contribution of 40 minutes from the membrane coverings from Table 5.2. It should be noted that to achieve the assigned fire endurance rating, the exterior side must be protected in accordance with Table 5.5. or any membrane that is assigned a time of at least 15 minutes as listed in Table 5.2.



EXAMPLE #2

Determine the fire endurance rating of a floor/ceiling assembly (shown below) having wood joists spaced 16 inches and protected on the bottom side (ceiling side) with two layers of 1/2 inch Type X gypsum board and having a 1/2 inch plywood subfloor on the upper side (floor side).

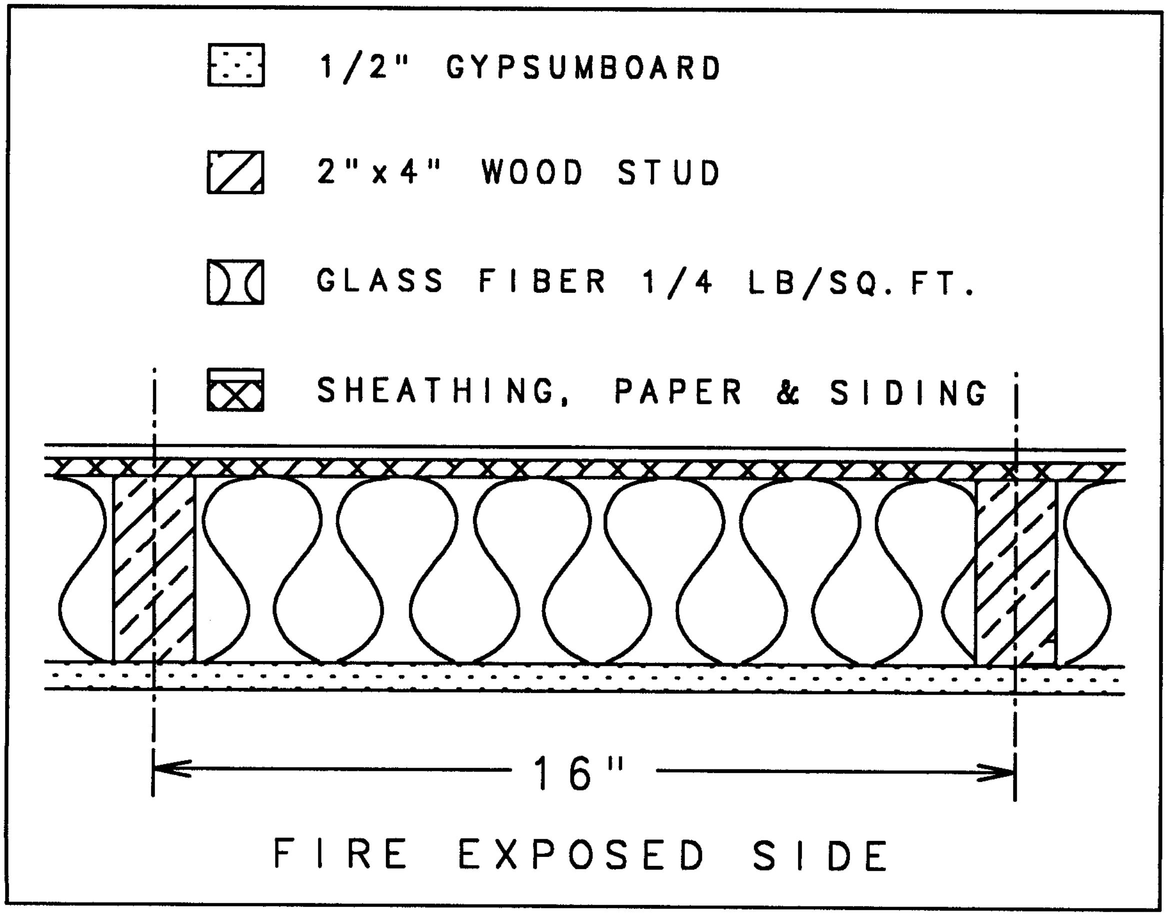
Table 5.2 shows the fire endurance time for each layer of 1/2 Type X gypsum board is 25 minutes. The fire endurance time assigned to wood joists, as shown in Table 5.3 is 10 minutes. Adding the assigned times of two layers of gypsum board and wood joists, a fire endurance rating of 60 minutes is calculated.



EXAMPLE #3

A private residence is being changed to an office. The load bearing exterior walls (shown below) of the residence consist of 2 by 4 inch studs spaced 16 inches on center, 1/2 inch gypsum board on the inside, and 5/16 inch exterior grade plywood, sheathing paper and 1/4 inch hardboard siding on the outside. The cavities between the wood studs are filled with 1/4 lb/sq.ft. glass fiber batt. The code requires the exterior wall of the structure to be upgraded to one hour fire endurance with fire exposure from the inside only. What modification can be made to comply with code requirement?

Table 5.2 shows the 1/2 inch gypsum board has a contribution to the assembly fire rating of 15 minutes. According to Table 5.3, the studs have an assigned time of 20 minutes. According to Table 5.4, the glass fiber does not contribute to the fire endurance of a load bearing wall. Thus, the fire endurance rating of the exterior wall of the residence equals 35 minutes. In order to upgrade the wall to one hour, a protective membrane should be added on the inside, contributing 25 minutes or more to the assembly rating. For example, a 1/2 inch Type X gypsum board adds 25 minutes according to Table 5.2, leading to a total of 60 minutes.



CHAPTER 6

WALLS

6.1. Introduction.

The structural behavior of wall assemblies when exposed to fire, is critical to the prevention of fire spread in a building. Model building codes, such as the *Uniform Building Code*, specify the hourly ratings for interior and exterior walls. Interior walls are intended to compartmentalize the interior space to prevent rapid smoke and flame movement while containing the fire within an area that does not exceed the capacity of the manual suppression forces. The exterior walls of the building are most often required to be rated only from the inside to protect neighboring structures from fire spread due to radiative heat transfer across open space. When spatial separation exceeds the distance beyond which fire will spread due to radiation, the walls may be unrated unless the building is of fire resistive construction.

Testing has shown that the least expensive and most common means of attaining a rated wall assembly is by applying gypsum wallboard to the stud face. This technique is commonly used in all construction group classifications from residential to assembly use. Care must be taken in the construction of rated wall assemblies. The field built wall must be identical to the wall listed by a testing laboratory and also meet the approval of the building official. Research has been performed on load bearing stud walls with a multitude of coverings.

6.2. Review of historic testing.

Early fire testing of load bearing walls was performed by McNaughton and Harrison [58]. The testing was initiated to determine the effect of insulation in prefabricated "stress-covered" wall and floor panels developed by the Forest Products Laboratory, Madison, Wisconsin. The findings reported were extensive, based on the number of wall configurations tested. In summary, the following conclusions were presented:

1) Plywood panels fabricated with phenolic resin glues provided a greater fire endurance than other glues, such as, soybean, casein and urea resin.
2) Insulation was found to have the greatest effect on increasing the fire endurance of walls. Batt insulation proved more reliable than loose or blown due to settlement.
3) The wider the space created by the stud, the greater the fire endurance.
4) The method of sealing the joint between abutting panels on the stud was critical to achieve high fire resistance ratings in heavily insulated walls.

The third conclusion is not recognized by the CAM because that procedure is conservative and does not provide the degree of sophistication necessary to account for such level of detail.

Work by Eickner [59] provides laboratory testing of wood frame walls exposed to the ASTM E 119. Although both sandwich and wood-frame assemblies were tested and reported in the literature, discussion herein is limited to the latter type. Following the ASTM E 119 fire exposure, a field test of these same assemblies was performed by

C. Holmes, et. al. [60]. The setting for these tests was a 3 room building, of rectangular plan. The long walls were loaded to the maximum allowable design load permitted by the 1971 *NDS* [61]. A total of 7 differing wall assemblies were tested, of which only 3 were of wood-frame construction.

The results of the ASTM E 119 laboratory tests and the field tests provide some insight into comparing the actual behavior of exterior wood-frame walls when exposed to fire. An average fire load of 4.4 lb/ft^2 between the wood-frame assemblies was close to 5.0 lb/ft^2 reported in surveys of residential occupancies. Air flow into the building was regulated such that a ventilation controlled fire would exist. It was the observation of the scientists that a ventilation controlled fire is more severe than a fuel-surface controlled fire. The literature reports the three assemblies as follows:

> "The fifth structure was of wood-frame construction, 2- by 4-inch hem-fir lumber, standard and construction grade, 16 inches on center (o.c) for framing the side walls, and 2- by 6-inch hem-fir lumber, standard and construction grade, 16 inches o.c. for the floor joists. The window, door and room partitions were located as in the sandwich structures. The wall and roof sheathing was 3/8-inch Douglas-fir exterior C-D plywood sheathing applied with six penny common nails, 6 inches o.c. at the panel edges and 12 inches o.c. at the intermediate locations. The walls and ceiling were insulated with 3-1/2-inch-thick glass-fiber roll insulation (R-11) stapled to framing edges facing the interior wall surface. The interior wall surface throughout the structure was of 3/8-inch-thick regular gypsum wallboard, fastened with 1-1/4-inch gypsum wallboard screws spaced 8 inches o.c. An extra layer of 5/8-inch type X gypsum wall board was applied to the ceiling to ensure that the failures in the walls would precede the roof failure and for saving of the roof for use in the additional structure tests. All wallboard joints were taped and covered with joint compound. The wall was painted with interior latex paint.
>
> The exterior of the two load-bearing side walls was covered with 1/2- by 6-inch-wide cedar bevel siding, nailed with seven penny siding nails. The siding was not painted.

> The sixth structure was the same as the fifth, except the sheathing was 1/2-inch regular-density wood-fiber sheathing panels nailed to framing with 1-1/2-inch galvanized roofing nails, spaced 3 inches o.c. Also, the east wall was protected on the interior with two layers of 3/8-inch gypsum wallboard. The roof-ceiling was a reuse of the assembly from Structure 5, with the ceiling protection renewed with two layers of 5/8-inch type-X gypsum wallboard.
>
> The seventh structure also was essentially the same as the fifth, except that the interior lining on the walls was 1/4-inch lauan plywood (PS 51-71), grooved and with simulated wood-grain finish on the surface. The plywood panels were nailed directly to the studs with 1-inch finish nails, 8 inches o.c. The ceiling was protected with 5/8-inch type-X and 3/8-inch gypsum wallboard. The 3/8-inch gypsum wallboard was also used as protection underneath the plywood wall lining on the east and west ends, to ensure that these walls would retain a sufficient amount of their integrity during the fire exposure to provide an adequate test of the two (north and south) load-bearing walls."

Structural failure was defined to occur when the large counter weight, which applied the load to the north and south walls, touched the ground. At this point, excessive deflection had occurred to these walls. Following is a summary of the ASTM E 119 laboratory tests and the analogous field tests:

TABLE 6.1

FIRE ENDURANCE AS TIME TO STRUCTURAL FAILURE						
Structure No.	**Wall section**					**ASTM E 119 tests**
	Northeast	**Southeast**	**Southwest**	**Northwest**	**Average**	
	min:sec	**min:sec**	**min:sec**	**min:sec**	**min:sec**	**min:sec**
5	**43:15**	**41:00**	**49:15**	**50:45**	**46:00**	**29:30**
6	**38:15**	**36:00**	**42:30**	**42:00**	**39:45**	**34:00**
7	**25:30**	**33:15**	**38 (est)**	**32 (est)**	**32:15**	**21:08**

The north and south exterior walls were divided in half and identified by the nomenclature of northeast and northwest, and southeast and southwest. The northeast and southeast walls were in a room which was open from the north wall to the south wall. The northwest and southwest walls were divided by an interior partition at the midpoint of the building width and separated from the larger room with interior partitions with a door opening.

The time to flashover was recorded for each of the test structures. For structure #5, with noncombustible wall linings, the time to flashover was 21:15 minutes. For structure #7, with combustible wall linings, the time to flashover was 18:00. The flashover time recorded in structure #6 was 14:30, but a prevailing wind was thought to have influenced fire growth. The authors did draw the conclusion that the presence of combustible wall lining did not contribute significantly to the time to reach flashover.

A series of tests were performed on the fire behavior of structural flakeboard by C.A. Holmes [62]. Four independently manufactured flakeboards, including the experimental Forest Service flakeboard and three commercial flakeboards were tested in load bearing wall assemblies in accordance with the ASTM E 119 fire exposure. For each board, two wall configurations were fabricated and tested. The first configuration utilized 3/8" gypsum wallboard attached to the furnace side of 2" x 4" studs spaced at 16" o/c. The opposite face, away from the fire, was sheathed with a 1/2" thickness of the particular flakeboard being tested. The second configuration was a symmetrical wall assembly, with both faces sheathed with a 1/2" thickness of the particular flakeboard.

The time to structural failure of the walls constructed with the first configuration ranged from 28:40 (min:sec) to 35:37, whereas, the second configuration, utilizing flakeboard on both faces, resulted in times ranging from 21:13 to 30:44. The time to burn through ranged from 27:45 to 33:54 for the first configuration and 26:20 to 31:35 for the second configuration.

In reporting the fire endurance of combustible wall assemblies, the "finish rating" is often listed. The finish rating is the time at which the average temperature rise, recorded on the edge of the stud facing the fire, reaches 250°F or a single reading exceeds 325°F. For the flakeboards tested, the finish rating ranged between 7.7 minutes and 10.4 minutes. The authors further stated:

> "...the flakeboard interior facing was observed to begin to break up between 11 and 12 minutes and to be almost completely gone in 14 to 16 minutes."

6.3. Component additive method

The American Forest & Paper Association's, *Design for Code Acceptance, No. 4*, [50] demonstrates the component additive method for calculating the endurance of wall assemblies. A discussion of this methodology and examples appear in Chapter 5.

CHAPTER 7

FIRE ENDURANCE OF BEAMS

7.1. Review of design methods.

In 1968, tests by Hall [63] were performed on 4 laminated beams subjected to an ASTM E 119 time vs. temperature fire exposure. The laminated beams approximately 5.5" x 9.0" in cross sectional dimension, spanned a distance of approximately 11'-10". The beams were braced against end rotation, with no intermediate bracing. The purpose of this fire test was to validate the approximate charring rate of 1.5 in/hr and to calculate the fire endurance based on this rate of charring.

Hall selected 300°C as the char base location. The beams were stressed to maximum allowable values for the test. To calculate the time to failure, Hall used the following equation, developed by Sunley:

$$Basic\,stress = \frac{mean - (2.33 \ x \ std.dev)}{2.25} \tag{27}$$

The expression on the right side of the equation is used to establish an allowable stress which is within the 1st percentile of samples with the same grade. This is analogous to the earlier discussion of the 5th percentile value, used in current design practice. The denominator is an adjustment factor which reduces the 1st percentile ultimate strength to an allowable stress, accounting for safety and long term loading.

By trial and error, Hall determined the reduced beam dimension and the corresponding moment of inertia which would provide the same moment resisting capacity as the original beam. The allowable stress for the reduced area beam was 2.25 times greater than the allowable stress used to compute the original bending moment. In theory, after a time period of approximately 43 minutes, at a charring rate of approximately 1.5 in/hr, the original beam dimensions had been reduced by approximately 1.08 inches on three sides.

Testing resulted in a time to failure of the first beam of 53 minutes. Hall suggested the 10 minute discrepancy is partially due to furnace warm-up time (4 minutes), inaccuracy associated with the factor of 2.25, and error associated with the charring rate.

Lie [45] presented a methodology, which had been partially derived by Imaizumi [64], for calculating the endurance of glued-laminated beams. Imaizumi suggested that two parameters were necessary to predict the behavior of beams. A variable, k, was necessary to associate the maximum allowable load to the actual load. A variable, α, was necessary to reflect the loss in strength of the uncharred cross section due to the effect of the increasing internal wood fiber temperature. Therefore, for a beam exposed to fire on four-sides, the critical depth, d, is determined from the expression:

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

where:
k = ratio of design load to ultimate load
α = strength reduction due to internal heating
D = depth (larger dimension, inches)
B = breadth (smaller dimension, inches)
d = reduced depth (inches)

When the critical depth, d, is known, the effective time to failure or the fire endurance of the beam can be calculated from the equation:

$$t_{b4}=\frac{D-d}{2\beta} \tag{29}$$

where:
t_{b4} = time in minutes to reach depth d (min.)
β = charring rate (in/min.)

Lie also developed this methodology for a beam exposed to fire from three sides, which is typical of a beam supporting floor or roof sheathing, where the top side of the beam is protected:

$$\frac{k}{\alpha}\frac{B/D}{B/D-2(1-d/D)}=(d/D)^2 \tag{30}$$

and the fire endurance can be calculated in a similar manner:

$$t_{b3}=\frac{D-d}{\beta} \tag{31}$$

Equations 29 and 31 are not readily solved since they both contain two unknowns in t_b and d. Lie developed a graphical solution, at various k values ranging from 0.2 to 0.5, utilizing a value of $\alpha = 0.8$ and $\beta = .0236$ in/min (1.42 in/hr). This range of k represents a factor of safety from 2 to 5. From the graph, approximate equations were derived in terms of the original breadth and depth. This format is significantly easier for the determination of time to critical depth. For a beam exposed to fire on three sides:

$$t_{b4}=0.85(B/k)[4-2(B/D)] \tag{32}$$

and for a beam with fire exposure on four sides:

$$t_{b3}=0.85(B/k)[4-(B/D)] \tag{33}$$

Lie recognized that the fire endurance of a beam is not linearly related to the ratio of ultimate to actual stress. For fire endurance, a linear reduction in load results in a non-linear increase in fire endurance. Lie proposed that a factor, z, shown in Table 7.1 be applied to compensate for the non-linearity associated with decreased loading.

TABLE 7.1

Value of z	
Load (as % of allowable load)	z
≻ 75	1.0
≤ 75, ≻ 50	1.1
≤ 50	1.3

Lie suggests the following approximate equations for the determination of time to failure, based on the graphic solutions, assuming a k = 0.33 and a charring rate of 0.0236 in/min. (1.42 in/hr.):

$$t_{b4}=2.54(z)(B)[4-2(B/D)] \tag{34}$$

for a beam with exposure on four faces and:

$$t_{b3}=2.54(z)(B)[4-(B/D)] \tag{35}$$

for a beam with exposure on three faces.

Lie suggested that such stresses induced by wind or earthquake loads can be ignored. He proposes that beams resisting snow loads use 50% of the required design load to determine the percentage of applicable stress. The probability of wind or earthquake loads occurring simultaneously with a fire is extremely low, whereas, some snow load is possible for roof beams during a fire, although melting of the snow would occur simultaneously. Two model building codes, *UBC* [55] and *SBC* [56] have incorporated Lie's approach with slight changes.

Fredlund [65] reported on the design of beams when lateral buckling restraint along the span is not provided. The procedure developed is sensitive to the end conditions of the beam, i.e. restrained or unrestrained and the opening factor developed by Pettersson [66]. The opening factor is a function of the opening area and opening height as a ratio of the wall area:

$$\frac{A\sqrt{h}}{A_{tot}} \tag{36}$$

Pettersson found the charring rate to be equal to 0.0236 in/min. (1.42 in/hr.) for an opening factor less than 0.25 in.$^{1/2}$. For an opening factor of 0.25 in.$^{1/2}$ to 0.75 in $^{1/2}$, the charring rate increases linearly; if greater than 0.25 in$^{1/2}$, it maintains a constant rate of 0.0394 in./min. (2.36 in./hr).

Fredlund determined the fire endurance of a simply supported laminated beam, 6" in width and 1'8" in depth. The beam spans 39.4' and carries a uniform load of 79.4#/ft. The opening factor of 0.08 $m^{1/2}$ produces an average charring rate of 1.89 inches/hr. When exposed to fire on three sides, the predicted time to failure based on the critical buckling moment is 26 minutes. Under pure bending, the predicted time to failure is 47 minutes. The theoretical 47 minute failure time is consistent with a relationship developed by Tenning [67] and also by Odeen [68] which states that the charring rate is constant up to the point where the depth of the char layer exceeds 1/4 of the original beam width. This recognizes that the influence of temperature and moisture become a factor from the opposing face. Similarly, for a beam exposed to fire on four sides, the unrestrained and pure bending time to failure are 18 minutes and 43 minutes, respectively. As a third example, the beam is laterally restrained at 6.6' intervals. The time to failure is predicted to be 50 minutes, assuming the bracing remains in place for the duration of the fire exposure.

In 1982, the National Forest Products Association [69] sponsored an ASTM E 119 test of an 8¾" wide by 16½ deep glued laminated beam The beam was loaded at quarter points such that the extreme fiber bending stress was 71.5% of the allowable design value. The beam was laterally braced on the compression edge at the center point. Time to failure under ASTM E 119 fire exposure was 86 minutes.

Bender, et al. [70] developed a model to predict the room temperature strength and stiffness of glued laminated beams. Due to high costs associated with full scale destructive testing of glued laminated beams, a model was developed which utilized computer generated random beam lay-ups, Monte Carlo simulations with of the layups included the component variables, modulus of elasticity, length of lamination and tensile strength of end joints. Good predictions were achieved for 8 and 10 lamination beams.

Once the model was found to be in agreement with full scale test results, modeling of cross section reduction was performed over time to simulate fire exposure. The thickness of the char layer which was considered lost to fire exposure was expressed as:

$$R=\beta t+\delta \tag{37}$$

where:
R = thickness of the char layer
β = charring rate.
t = exposure time.
δ = finite thickness of residual wood which is weakened by the elevated temperature and moisture.

Two loading conditions were selected that were 47.6% and 33.3% (k = 0.476 and 0.333) of the ultimate design capacity. The char rate β = 1/40 inch per minute and δ = 0.2 inches, were assumed based on previous work. Times to failure were calculated as 40.3 minutes (k = 0.476), with a COV of 11.9 percent and 53.1 minutes (k = 0.333), with a COV of 8.9 percent. These results compared well with results based on Lie's equation which predicted times of 39 minutes and 54 minutes, respectively.

Schaffer, et al. [71] performed additional validation of the earlier work by independently testing 21 glued-laminated beams and comparing those results to the model developed by Bender discussed earlier. Schaffer concludes that "the model of beam strength appears acceptable and possibly slightly conservative."

Using results published by Schaffer [71], King and Glowinski [72] developed a computer model for predicting time to failure of a beam exposed to fire, based on the transformed section theory. The model is valid only for beams exposed to fire on three sides. For the particular application of this program, the transformed section theory assumes 4 layers of wood with varying strength and stiffness properties. The outer most zone is the char layer, progressing towards the center of the beam is the

hot layer, warm layer and cold layer. The mean modulus of elasticity and ultimate strength values of the cold zone, E_1 and F_{b1} respectively, are equal to the room temperature value for the grade and species of wood. The warm layer ratio for E_2 and F_{b2} are 0.90 and 0.80, respectively. The hot layer ratios for E_3 and F_{b3} are 0.75 and 0.60, respectively. The char layer is assumed to have zero strength properties.

The thickness of the char layer was expressed using two equations. It has been shown by Schaffer that a steady-state charring rate does not occur until 15 to 20 minutes following the start of fire exposure. King and Glowinski chose to assume that after 15 minutes, the charring rate decreases and developed the following equation for the initial char layer thickness (t) as 4/3 the steady-state rate:

$$t = \frac{4}{3}(\beta)(m), when \ m \leq 15 \tag{38}$$

After 15 minutes, the char layer thickness is expressed as:

$$t = \frac{4}{3}\beta(15) + \beta(m-15) \ when \ m > 15 \tag{39}$$

where:
t = thickness of the char layer
β = charring rate (in/min)
m = elapsed exposure time (min)

This latter rate accounts for the insulating effect of the forming char layer. The thickness of the warm and hot zones are assumed to increases exponentially with time, in accordance with the equation:

$$q = 2(1 - e^{-0.07685m}) \tag{40}$$

The heated zone is comprised of a hot zone, assumed to be 1/3 of the total elevated layer thickness with the remaining 2/3 assigned to the warm zone. The cold zone thickness is the original width and depth of the beam minus the sum of the char layer and heated zone thicknesses.

At each 0.1 minute time step, the beam is checked for failure. Each zone or part thereof of the beam must be checked for loss of strength. Loss of the bottom, outer most tension zone of the hot layer may not result in failure since the load can be carried by the remaining sections. In all, 36 possible failure sequences are checked for both tension only and tension and compression failures.

7.2. Design example.

In private correspondence from Janssens [73], equations are derived for the curves which define the load factor, z. The equation was derived by digitizing the curves in the AF&PA publication. For beams, z is to 1.3 when r is equal to or less than 50. When r is greater than 50, $z = 0.7 + 30/r$.

EXAMPLE

A two story office building is required to be of Type 5A construction. The building is 35' wide and 60' in length. Repetitive framing members span from the exterior walls to a glued laminated beam at the center the building. Two simply supported beams, each 30' in length, bear on the exterior walls and a column at the center of the building. The beam is of greater depth than the floor/ceiling system, therefore a portion of the beam will be left exposed beneath the rated floor/ceiling assembly.

Determine the fire endurance rating of the beam selected to carry the imposed loads. Extreme fiber in bending F_b is given as 2400 psi and the species is Douglas- Fir.

Live load = 50 $\#/ft^2$; Dead load = 15 $\#/ft^2$

w = 65$\#/ft^2$ x 17'-6" = 1137.5 #/ft.

Moment = $wl^2 \div 8 = 1.536 \times 10^6$ #in.

Sreq'd = 640 in^3

Try a 8¾" × 24"; S_{actual} = 840 in^3

Check volume factor [1991 *NDS*]

$C_v = 0.85$

$S_{actual}/C_v = 753\ in^3 < 840\ in^3\ \therefore$ O.K.

Calculate the load ratio:

$r = 753in^3/840in^3 = 90\%$

Calculate the load factor:

$z = 0.7 + 30/r = 1.035$

Calculate t from Eq. 37:

$t = 2.54\ zb\ [4-(b/d)] = 2.54(1.035)(8.75)[4-(8.75/24)]$

time to failure = 83.6 minutes > 60 minutes $\therefore$ O.K.

Eliminate one core laminate and add one outer tension zone laminate to the bottom of the beam.

7.3. Live load reduction factor.

When using the beam methodology, it is appropriate for the designer to apply live load reduction factors when permitted by the building code official. For beams supporting large floor areas, the probability of full floor live load occurring together with a fire would be reduced. The *NBC* [11] provides the following live load reduction factor when the tributary area exceeds 400ft^2:

$$L = L_o(0.25 + \frac{15}{\sqrt{A_i}}) \tag{41}$$

where:
L = reduced design live load in pounds per square foot.
L_o = unreduced design live load per the code.
A_i = influence area in square feet, taken as four times the tributary area for a column, two times the tributary area for a beam and the panel area for a two- way slab.

For example, a beam in an office building supporting a required live load, L_o = 50 #/ft^2 and a tributary area of 500 ft^2, would have a calculated L = 36.2 #/ft2 or 72% of the design. In no case may the L be less than 50% of L_o for members supporting one floor nor 40 percent for other members.

CHAPTER 8

COLUMNS

8.1. Review of design methods.

Early testing of the fire resistance of columns was performed by Malhotra and Rogowski [24]. Sixteen glued laminated columns of four species were fabricated using four different adhesive types. Additionally, three shape factors were investigated with three levels of applied load. Since it was not possible to test every combination of species, adhesive, shape and load, a statistical analysis was performed on the 16 full scale tests to develop an empirical model. The model for calculating time to failure, t (minutes), takes the form:

$$t = T \; x \; G \; x \; S \; x \; L \tag{42}$$

where the variables are given in Table 8.1

All columns had a cross-sectional area of 81 in.^{2} and a length of 11.8 ft. Maximum allowable loads were calculated based on fixed end conditions. The effect of species on fire endurance was found to be directly related to wood density as they are listed in Table 8.1 from greatest to least. Synthetic adhesives were shown to perform better the natural casein under fire exposure.

TABLE 8.1

EMPIRICAL VALUES OF FACTORS TO DETERMINE FIRE RESISTANCE OF COLUMNS	
<u>T (species)</u>	
Douglas-fir	2.64
European redwood	2.56
Western hemlock	2.33
Western red cedar	2.06
<u>G (Glue)</u>	
Phenolic	2.64
Resorcinol	2.48
Urea	2.43
Casein	2.17
<u>S (Section shape)</u>	
α: b/d = 1.00	2.64
β: b/d = 1.74	2.46
δ: b/d = 2.71	2.04
<u>L (Load)</u>	
100% design load	2.64
50% design load	3.74
25% design load	5.28

A simple expression was derived to relate the change in d (depth) to fire endurance, where time to failure is proportional to $d^{0.7}$. Testing was also performed on glued laminated columns which contained lower grade laminates. The findings indicate that grade had little effect on time to failure due in part to the lower allowable loads.

Three load levels of 25%, 50% and 100% were tested to determine the correlation between the level of stress and the time to failure. Loading was found to be inversely proportional to the square root of the percentage of allowable load.

Lie developed an equation to predict time to failure based on the approach utilized for 4-sided beams. Lie derived equations for determining the critical depth of short and long columns. For short columns the expression takes the form:

$$\frac{k}{\alpha}\frac{B/D}{d/D-(1-B/D)}=\frac{d}{D} \tag{43}$$

where:

k = percent of allowable load
α = reduced design values due to heating
B = original breadth (larger size)
b = reduced breadth
D = original depth (smaller size)
d = reduced depth

For long columns, Lie uses Euler's formula, where p′ equals the buckling load:

$$p'=\frac{\pi^2 EA}{(L/r)^2} \tag{44}$$

where:

E = modulus of elasticity
A = cross sectional area
L = unbraced length
r = radius of gyration

The radius of gyration is a function of the depth, D, such that:

$$r=\frac{D}{\sqrt{12}} \tag{45}$$

Therefore, the right hand expression of equation (5), (d/D), as derived for the short column is raised to the third power to describe the critical depth of a long column governed by Euler's formula:

$$\frac{k}{\alpha}\frac{B/D}{d/D-(1-B/D)}=(\frac{d}{D})^3 \tag{46}$$

where:
k = percent of allowable load
α = reduced design value due to heating
B = original breadth (larger size)
b = reduced breadth
D = original depth (smaller size)
d = reduced depth

The equation which represents the time to failure of the column as a function of the charring rate and the loss of cross sectional area is:

$$t_{c4}=\frac{(D-d)}{2\beta} \tag{47}$$

where:
t_{c4}= time to failure with four sides exposed
D = original depth
d = reduced depth
β = charring rate

Examination of the preceding short and long column formulas reveal, the exponent to which the expression (d/D) is raised is critical in determining the behavior of the column. Lie chooses to provide a graphical solution to the equation derived on using an exponential value of n=2. This is interpreted as an average value, typical of an intermediate length column. A value of α = 0.80 was selected to describe the effect of strength loss due to internal heating of the column fibers. The graph, presented in terms of B/D, allows for the determination of the critical depth, at values of k from 0.2 to 0.5, from the expression t_{b4}/D. This range of k represents factors of safety from 2 to 5. Since the solution is presented in terms of D it requires a trial and error solution to determine t_{b4}. To eliminate the need for a trial and error solution, Lie presents an approximate solution to the curves in the metric form:

$$t_{c4}=0.85(\frac{D}{k})[3-\frac{D}{B}] \tag{48}$$

This model closely follows the curves for values of k = 0.3 to 0.5 and is reasonably accurate for a value of k=0.2.

Lie compared equation 48 using a k=0.33 with results from glued laminated column fire tests. In general, the assumptions made by Lie, i.e., factor of safety of 3 and n=2, overestimate the failure time of long columns and underestimate the failure time of short columns.

Lie's final model for the calculation of time to failure of columns heated on four sides refines the previously discussed variations in predicting failure time by introducing an empirical factor, z. The value for z appear in Table 8.2.

Lie suggests the following equation for the calculation of columns heated from four sides:

$$t_{c4} = 2.54(z)(D)[3-(D/B)] \tag{49}$$

Schaffer [74] suggests that the equations previously presented should not be utilized when the l/r value is less than 100. This corresponds to an l_e/d of approximately 29, which is quite close to the intermediate vs. long column interface given in the 1986 *NDS* [7], depending on the strength and stiffness of the species and grade.

TABLE 8.2

VALUES OF z FOR COLUMNS		
Load (as % of allowable load)	Column Slenderness Ratio	
	L/D > 10	L/D ≤ 10
> 75	1.0	1.2
≤75, > 50	1.1	1.3
≤ 100	1.3	1.5

As discussed in the Beam chapter of this paper, two of model building codes have fire endurance calculation procedures for heavy timber within the text of the code. Provisions for the determination of column fire endurance are also contained therein.

8.2. Design example.

In private correspondence from Janssens [73], equations are derived for the curves which define the load factor, z, for the two Kel/d ratios. The equations were derived by digitizing the curves in the NFPA publication. For columns having a $K_el/d \leq 11$, z is equal to 1.5 when the load ratio, r is equal to or less than 50. When r is greater than 50, $z = 0.9 + 30/r$. For columns were the $K_e l/d > 11$, z is to 1.3 when r is equal to or less than 50. When r is greater than 50, $z = 0.7 + 30/r$.

EXAMPLE

The column supporting the glued laminated beams in the previous example is to be left exposed. A 8.75" x 9" Douglas-Fir glued laminated column has been specified. The column length is 8'-0".

Determine the fire endurance rating of the column selected to carry the imposed loads.

$F_c = 875$ psi; $E = 1{,}500{,}000$ psi

Area = 78.75 in^2; Column load = 34,125 lbs.

Calculate the required compressive stress:

$F_{creq'd} = 34125\# / 78.75 \text{ in2} = 433$ psi

Calculate the effective length:

$l_e = 8'(12) = 96$ inches

Determine the effective length factor [1991 *NDS*]

$K_e = 1.0$

Calculate the column stability factor [1991 *NDS*, Eq. 3.7-1)

$C_p = 0.982$

Calculated adjusted Fc':

$F_c' = 875 \text{ psi} \times 0.982 = 859 \text{ psi}$

Calculate load ratio:

Load ratio, $r = 433/859 = 0.504$

Calculate slenderness ratio:

$K_e l_e/d = 1 \times 96''/8.75'' = 10.97$

Calculate the load factor:

$z = 0.9 + 30/r = 0.9 + 30/50 = 1.5$

Calculate the time to failure from Eq. 52:

$t = 2.54zd\ [3-(d/b)]$

$t = 2.54(1.50)(9)[3-(9/8.75)] = 67.5$ minutes $\therefore$ O.K.

CHAPTER 9

MECHANICAL FASTENERS, ADHESIVES AND COATINGS

9.1. Mechanical fasteners.

Building codes recognize construction of buildings utilizing heavy timbers as a specific type of construction. Prescribed requirements exist to assure that columns, beams, roof deck and floor deck, meet or exceed a minimum dimension. The heavy timber building has historically been recognized as having a one-hour fire endurance rating for the structural frame.

Although the fire performance of these timber members is quite predictable, attention must be given to connectors and fasteners. Failure of exposed metal connectors can result in premature failure of the structural frame. To prevent this, building codes require that all materials used in the structural frame, other than wood members meeting or exceeding the minimum dimensions, have a one-hour fire endurance rating. This includes all load bearing elements, such as steel lintels.

Jonsson and Pettersson [75] report on work performed in Germany by Kordina and Meyer-Ottens [76] to evaluate protection requirements for glued laminated column to beam connections. This work provides minimum thicknesses of wood "cover sheets" over nailed or bolted connections. The thickness of the required wood cover is dependent upon the hourly rating which must be achieved. The unprotected nailed gusset plates used in the study have a rating of approximately 25 minutes. Protection of the nail heads by a 35mm thick "cover sheet" provides a one-hour fire endurance rating.

In a two part program sponsored by the Building Research Association of New Zealand, Yiu and King [77] performed studies of unloaded nailed plywood or metal gusset plate connectors. The connections were exposed to the ISO 834 time temperature fire exposure for one-hour. The results conclude that:

> "either a 40mm solid timber or two layers of 14.5 mm thick paper-faced gypsum plasterboard were likely to achieve a one hour FRR on plywood and steel gussets." [78]

Lim and King [78] performed time temperature exposure tests on loaded butt spliced beam connections. The beams cantilevered beyond opposite furnace walls which acted as bearing points. Loads were suspended from the cantilevered ends, producing a negative moment at the splice within the test chamber, to simulate a knee joint in a portal frame. The test furnace held three beams simultaneously. Where the joints were protected by gypsum board, all four sides of the beam were encased. The results are shown in Table 9.1.

Failure in test 1 occurred at 50 minutes in beam X2, which is the center beam in the test assembly. The failure did not occur at the connection, which, with the plywood gusset removed, showed no evidence of charring or nail slipping in the joint.

TABLE 9.1

TEST RESULTS OF VARIOUS GUSSET METHODS OF PROTECTION						
Beam ID	**Beam Depth (mm)**	**Type of Protection**	**Gusset Material**	**Nail Load (x Basic)**	**Applied Moment (kN-m)**	**Timber Stress (Mpa)**
Test 1 - X1	540	2 layers gypsum board	30 mm Plywood	1.8	26	11.3
Test 1 - X2	540	2 layers gypsum board	30 mm Plywood	1.2	17	7.4
Test 1 - X4	630	2 layers gypsum board	30 mm Plywood	1.2	20	6.1
Test 2 - X3	540	1 layer gypsum board	30 mm Plywood	1.2	17	7.4
Test 2 -W1	540	1 layer gypsum board	5 mm Mild Steel	1.2	15	6.5
Test 2 -W2	540	intumescent coating	5 mm Mild Steel	1.2	15	6.5

Notes:

1) All beams 135 mm wide
2) The 30 mm plywood gussets comprised a layer of each of 12.5 and 17.5 mm Red pine construction plywood complying with NZS 3614 (SANZ 1971) with a moisture content of 11%.
3) The proprietary intumescent paint coating was applied as the maximum recommended by the manufacturer.

Failure in test 2 again occurred to the center of the three beams, W2, this time at 53 minutes. The mode of failure was cracking of the beam, remote from the point of splicing.

9.2 Adhesives

The use of adhesives in structural applications has increased dramatically during the latter part of the 20th century. Due in part to the development of synthetic adhesives during WWII, the utilization of bonded structural elements such as, glued laminated lumber (glulam), Laminated Veneer Lumber (LVL), plywood, oriented strand board (OSB) and particleboard has seen wide public acceptance.

The FPL *Wood Handbook* lists eleven adhesives suitable for structural applications. The continued specification of laminated structural elements is valuable to the wood industry. Due to the decline in naturally available larger solid sawn dimensional lumber, laminated elements will become increasingly popular. Since laminated elements can be manufactured from smaller dimensional sizes, second and third growth timber can be fully utilized.

The behavior of glued laminated lumber (Glulams) when exposed to fire has been proven by testing. Glulams are constructed of 1 or 2" thick wood lamination with finger jointed end splices. More recently, variations in the manufacturing of plywood has introduced laminated elements which are similar in load carry capacity to solid sawn 2" x 10"s and 2" x 12". Unlike plywood, where the adjacent veneer grains are perpendicular to each other, LVL has the grains of all veneers parallel. The veneers are 1/10" to 1/8" in thickness, in contrast to the thicker laminates of glued laminated timbers.

A product gaining rapid acceptance which uses LVL lumber is the I-joist. The product takes the shape of the letter "I", with the web consisting of structural panels and the chord of LVL. This configuration provides a high strength to weight ratio structural element.

The behavior of some adhesives when exposed to direct flame impingement has been studied by Schaffer [79]. One inch thick laminated slabs, resembling cutting boards, were exposed to the flame of a bunsen burner for 10 minutes. The flame temperature was approximated to be in the range of 800 -900°C. A model was developed to rank the adhesives in order of behavior. Schaffer provides the results in Table 9.2, based on the loss of adhesive perpendicular to the charred face.

9.3. Coatings.

Traditionally, enhanced fire performance of lumber and plywood requires that chemical solutions be impregnated into the fiber. The American Wood Preservers' Association maintains a book of standards which establish procedures for pressure treating lumber [80] and plywood [81] with fire retardant chemicals. The building codes establish the performance requirements for these materials. Generally, fire-retardant pressure treated wood must achieve a Class A flame spread in accordance with ASTM E 84 [82] and show no progressive combustion 10 feet beyond the centerline of the burner after 30 minutes of exposure.

In lieu of pressure impregnation of the fire retardant chemicals, which has been

TABLE 9.2

BEHAVIOR OF SELECTED ADHESIVES WHEN EXPOSED TO DIRECT FLAME IMPINGEMENT		
Group	Douglas -fir	Southern pine
Maintained bond throughout the pyrolysis and normal wood zones.	Melamine	Melamine
	Phenol-resorcinol	Phenol-resorcinol
Maintained bond throughout the normal wood zone.	60% Melamine 40% urea	60% Melamine 40% urea
	Urea, Casein[1]	Urea
		Casein
Bond separation occurring in the normal wood	Polyvinyl	Polyvinyl

1) Urea and casein are ranked the same in Douglas-fir due to small differences in their degradation indices in the species.

shown to reduce to strength of the of lumber or plywood, surface coatings have been introduced. White [83] performed small scale non load-bearing fire tests to determine the effect of various surface coatings applied to plywood. The research was two-fold: 1) coatings were evaluated to determine whether improved fire resistance (endurance) could be achieved and 2) coatings were evaluated to determine whether improved fire retardance (spread) could be achieved. Eight different chemical formulations where tested, four for fire resistance and four for fire retardance. Control samples of untreated plywood in thicknesses of 1/4", 5/8" and 3/4" established the baseline for comparing coated plywood results. Using ASTM E 119 fire exposure, the 508- by 508-mm (20- by 20-in.) plywood sheet was backed by a foam plastic slab and attached to a wood frame. Failure was achieved when the unexposed plywood surface temperature rise reached 139°C (250°F) or any one thermocouple reached 181°C (325°F).

Three tests of each thickness of untreated plywood exhibited the following mean total time to failure when exposed to the ASTM E 119 fire curve: 1/4" - 210 sec., 5/8" - 670 sec., and 3/4" - 870 sec. All coatings tested increased the time required to achieve failure, with thicker coatings performing better. Overall, the fire retardant coatings achieved a mean total time to failure ranging from 780- to 1580 sec. The fire resistance coatings achieved a mean total time to failure ranging from 930 to 3320 sec.

White points out a number of concerns with the test results. Because the scale of the test is small, full-size testing is necessary to gain reliable results. The orientation of the panels for the test is vertical where floor/ceiling assemblies could result in horizontally exposed surface areas.

CHAPTER 10

A PROCEDURE FOR USING EXPERT JUDGMENT TO PREDICT ASSEMBLY FAILURE

10.1 Introduction

The *Building Firesafety Engineering Method* [84] uses expert judgment and actuarial and statistical data to assign probabilities to the success or failure of sequential fire growth and extinguishment events. The methodology determines a building's ability to withstand fire or limit its growth. Consideration is given to all aspects of the building's fire defense system including; suppression systems, alarm systems and barrier performance. While actuarial and statistical data exist for predicting the reliability of sprinklers and detectors, little data exists on barrier performance in real fire exposures. The use of expert judgment techniques to predict barrier performance can supplement the method.

The purpose of this chapter is to present and evaluate a procedure which uses expert judgment to assign probabilities to the expected performance of an assembly exposed to fire. Using subjective reasoning aided by "best fit" empirical methodologies, experts knowledgeable in structural and fire protection engineering use their background to predict when the assembly will fail. Carefully planned scenarios introduce varying live and fuel loads, thus challenging the experts to rationalize their responses based upon these variations.

In the absence of computer models to simulate these variations, expert judgments can be useful if bias is identified. Due to time constraints and the effort involved by the experts, a thorough survey has not been completed as part of this paper. Conclusions and pitfalls are provided to give others the opportunity to benefit from this exercise if similar work is continued.

10.2. Procedure for an expert survey.

The procedure for conducting an expert judgment survey is presented in the context of predicting assembly performance. The steps described herein were used by the author to conduct the survey contained in Appendix A. This survey was developed as an example to aid reporting of these procedures. Each step of establishing, executing and refining the survey follows, with an explanation and description of its relationship to the example.

10.2.1. Purpose

Step #1 - Define the purpose of the exercise, establishing parameters which will keep the experts focused on the question.

It is essential that the experts have a clear understanding of the purpose and have the ability to revisit it during the course of the exercise. Without clear guidelines, the experts are likely to introduce their own parameters, thus creating inconsistencies between