Chapter Four:
Post-Fire Assessment of structural Wood Members

Since the interior of a charred wood member normally retains its structural integrity, large structural wood members often do not need to be replaced after a fire. Engineering judgement is required to determine which members can remain and which members need to be replaced or repaired. Due to the lack of established methods to directly determine the residual capacity of damaged wood members, a systematic approach starting with the assessment of the likely fire exposure is recommended. Assessment includes visual inspection of damaged members, visual inspection of connections, and visual inspection of any protective membranes (i.e., gypsum board). Potential methods for nondestructive evaluation of structural properties of a fire-damaged wood member are discussed after a brief review of the degradation of wood when exposed to fire.

Thermal Degradation of Wood

Wood degrades when exposed to elevated temperatures. Fire exposure causes the thermal degradation or pyrolysis of wood in which the wood is converted to volatile gases and a char residue. The extent of any thermal degradation depends on both the temperature and the duration of the exposure. At temperatures below 100°C (212°F), the immediate effect of temperature on mechanical properties of wood is essentially reversible (Green et al. 1999), Prolonged exposure to temperatues exceeding 65°C (≡150°F) can result in permanent losses in strength properties (AF&PA 2001).Degradation resulting in weight loss is associated with temperatures exceedlng 100°C. For temperatures less than 200°C (≡392°F), charring of the wood requires prolonged exposure. Significant degradation occurs in the temperature range of 200° to 300°C (392° to 572°F). A temperature of ≡300°C (≡550°F) is commonly associated with the base of the char layer for wood subjected to direct fire exposure in the standard fire-resistance test. Vigorous production of flammable volatiles occurs in the temperature range of 300° to 450°C (550° to 842°F)., Kinetic parameters are used to model the rate of thermal degradation, Detailed discussions of the processes involved can be found in the literature (Browne 1958, White and Dietenberger 2001).

Sudden surface heating of a wood member in a fire results in surface charring and a steep temperature gradient. Thus, the stages of thermal wood degradation previously discussed become zones of degradation in a structural wood member exposed to fire. In a broad sense, there is an outer char layer, a pyrolysis zone, a zone of elevated temperatures, and the cool interior **(Fig. 4.1),** These zones of degradation reflect the temperature profile through the cross section.

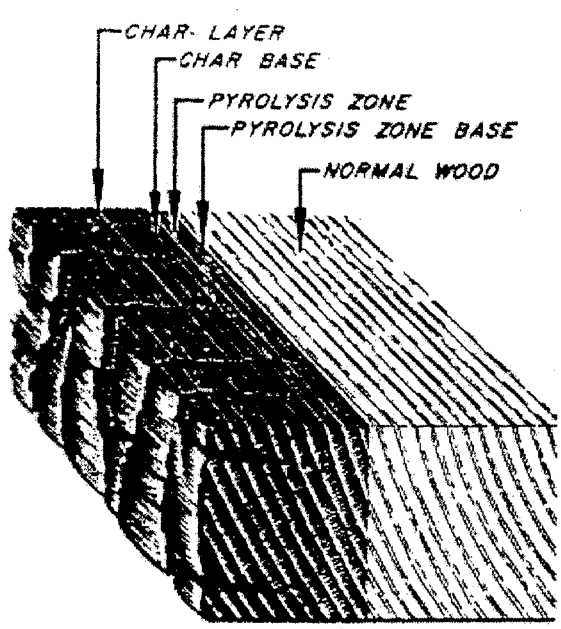


Figure 4.1.—*Illustration of the degradation zones in a charred piece of wood.*

Fire Damaged Wood

For wood members that have charred, the char layer can be easily scrapped off. Obviously, any charred portion of a fire-exposed wood member has no residual load capacity. The wood beneath the char layer has residual load capacity; but, this residual capacity will be less than the load capacity prior to the fire. Members that have only visual smoke damage or slight browning of the surface also have significant residual load capacity.

ASTM E 119 (ASTM International 2000) standard test method is the test for determining the fire-resistance rating of a structural member or assemblies for building code purposes. This severe and direct fire exposure results in rapid surface charring, the development of a char layer with a base temperature of -300°C (-550°F), and a steep temperature gradient of 177°C (350°F) at 6 mm (0.2 in.) and 104°C (220°F) at 13 mm (0.5 in.) beneath the char layer (**Fig. 4.2**). The standard fire exposure is a specifled time-temperature curve of 538°C (1,000°F) at 5 minutes, 843°C (1,550°F) at 30 minutes, and 927°C (1,700°F) at 1 hour. For a large wood member directly exposed to the standard fire exposure, the char rate is approximately 0.6 mm/min. (38 mm/hr., 1.5 in./hr., 1/40 in./min.). Char rate in the standard test depends on species, density, moisture content, and duration of exposure (White and Norheim 1992). Most research on fire endurance of wood members has been directed toward predicting or understanding their performance in this test (White 2002, Buchanan 2001). Fire endurance research on wood for other fire exposures or post-fire situations is limited.

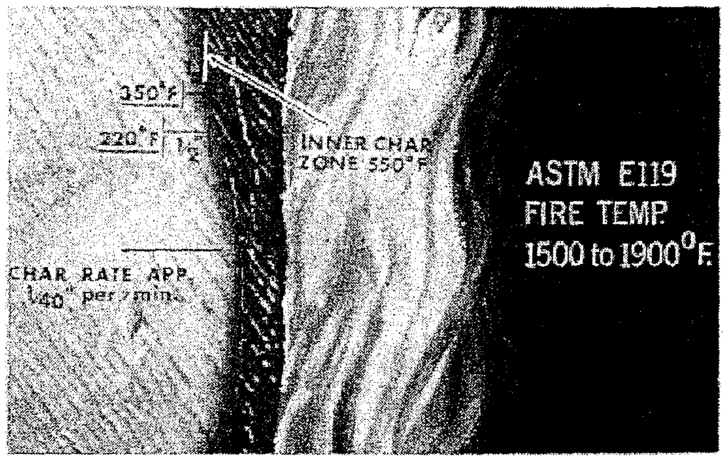


Figure 4.2.—*Illustration of a charring wood member exposed to the standard fire exposure of 815° to 1,038°C*

Standard fire exposure represents the exposure of a structural member or assembly in the immediate vicinity of a fully developed post-flashover fire. The following situations:

a. exposure of wood components a distance a way from the fully developed post-flashover fire (e.g., roof rafters exposed to hot gases from a fire in a room below);
b. smoldering cellulosic insulation fire near wood rafters;
c. high intensity fire that is quickly extinguished;
d. prolonged heating of wood after extinguishment; and
e. wood behind gypsum wallboard or other protective membranes

are all examples of fire exposures inconsistent with an assumption of the standard fire exposure. The general rules for reducing the cross section ror a fire equivalent to the standard exposure are based on assumptions of the temperature gradients within the uncharred wood during the fire. For this reason, it is advisable to first obtain an informed understanding of the fire itself and the fire exposure to the structural members being evaluated.

Fire Investigation

As noted by Buchanan (2001), it is valuable to visit the fire scene immediately after the fire to make notes of all of the damage that occurred. The post-fire situation dfter the mid-1990s fire in a building at the USDA Forest Service, Forest Products Laboratory is illustrated in **Figure.4.3.** For most fire investigations conducted by fire departments and other in-

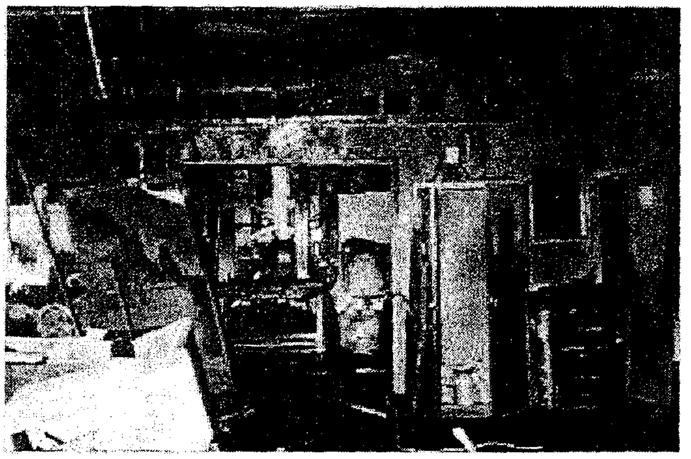


Figure 4.3.—*Area of fire origin in Building 2 fire at the Forest Products Laboratory,*

vestigators, the intent is to establish the cause for initial ignition and fire growth. The standard guide for such investigations is NFPA 921 *Guide for Fire and Explosions Investigations* (NFPA 1998). This guide advocates a methodology based on a systematic approach and attention to all relevant details. For the puropse of a post-fire assessment of structural wood members, the intent of an immediate investigation is to better estimate the intensity and duration of the fire exposure to the wood members during and after the fire. Such insight will be helpful in making engineering judgments on the likely temperatures within the charred and uncharred wood members. NFPA 921 provides information on various observations for estimating temperatures developed during a fire.

Without extinguishment, a fire has three phases:

1. the growth of the fire from ignition to flashover;
2. the fully developed post-flashover fire; and
3. the decay period of declining temperatures as the fuel is consumed.

The fire exposure of the standard fire-resistance test only approximates the second phase, or post-flashover portion, of the fire. Flashover is the full involvement of the combustible contents of the compartment and is associated with flames coming out of the door in the standard room-corner test. Information gathered in a NFPA 921 investigation will help establish likely maximum temperatures in various locations.

For the post-fire assessment, the exposure of the structural wood members to elevated temperatures during the decay period of fire development should be considered. While temperatures are lower during the decay period, the duration of exposure can be prolonged compared with the duration of the fully developed post-flashover fire phase. The steep temperature gradient near the fire-exposed surface assumed in the normal assessment of residual load capacity is based on transient heating coupled with progressive charring of the wood cross section. During prolonged cooling, surface temperatures will decline while temperatures on the cool inside portion of the cross section will increase. Tests have indicated that this temperature increase in the interior of a wood member due to re-distribution of heat after fire exposure is particularly the case for wood protected with gypsum board. Since the decay or post-extinguishment period is one of reduced temperatures, many damage observations made at the fire scene will be less helpful in determining the vations and duration of the exposure. More careful and detailed inspections of structural members and connections will likely need to be done in a subsequent inspection when the general debris has been removed.

Visual Inspection of Charred Members

Wood exposed to temperatures in excess of -300°C (-550°F) will form a residual char layer on the surface (**Fig. 4.4**). With prolonged exposure, charring of wood can occur at lower temperatures. While it retains the anatomical structure of uncharred wood, the char layer can be easily scraped or sand-blasted off.

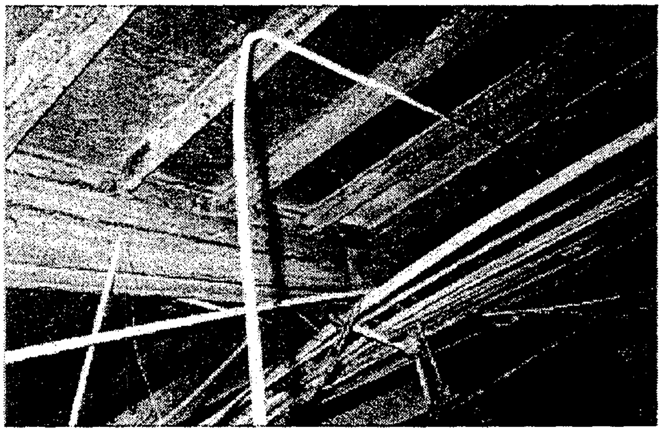


Figure 4.4.—*Charred and uncharred wood members in the Building 2 fire at the Forest Products Laboratory.*

In an inspection of charred members, it is important to understand that the char layer exhibits significant shrinkage. The shrinkage results in fissures in the char layer. Glowing combustion of the char also can occur. As a result, the thickness of the residual char layer is less than the depth of charring (**Fig. 4.5**). The profile of the original section will need to be determined from construction records or similar uncharted members.

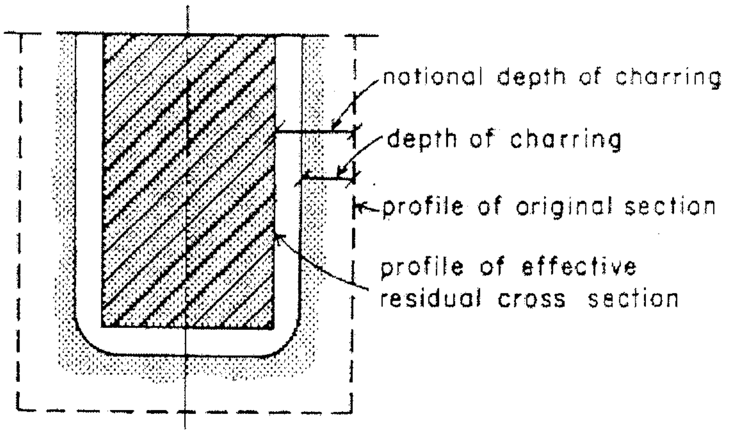


Figure 4.5.—*Illustration of the residual cross section of a charred wood member.*

Load Capacity of Damaged Members

Thermal degradation of wood results in the loss of structural properties. Thermal degradation of wood is a kinetic process. Due to the thermal properties of wood, a distinct temperature gradient develops in a wood member when it is exposed to fire. Thus, the loss of structural properties of fire-damaged wood members depends on both the temperature within the wood member and the duration of the elevated temperatures.

For an exposed wood member large enough that the temperature of its center or back surface has not increased, the temperature gradient within a wood beam or column for the standard fire exposure has been documented. For such a fire exposure, there is a clear demarcation of the base of the char layer. For the standard fire esposure of a semi-infinite slab, the temperature profile beneath the base of the char layer can be approximated by:

$$T = T_i + (T_p - T_i)(1 - x/a)^2 \qquad \textbf{[4.1]}$$

where:

T_i = initial temperature of the wood (°C)

T_p = temperature of the base of the char layer (300°C)

x = distance beneath the char layer (mm), and

a = thickness (mm) of the layer of elevated temperatures (**Fig. 4.6**).

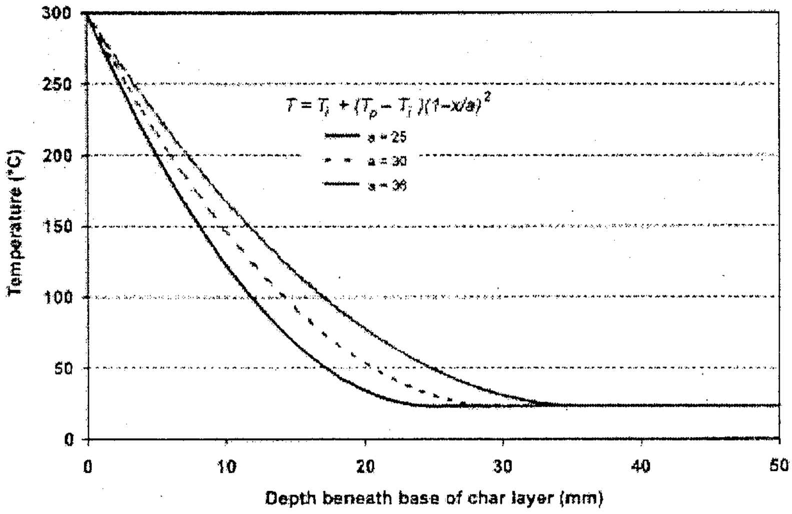


Figure 4.6.—*Temperature profile beneath the base of the char layer of a semi-infinite wood slab directly exposed to the ASTM E 119 standard fire exposure.*

For the data of White and Nordheim (1992), the average value of a was 33 mm (1.3 in.) for the eight species tested (Janssens and White 1994). An alternative exponential model was developed by Schaffer (1965, 1982b). This temperature profile is valid after a standard fire exposure of about 20 minutes. The thickness of the zone of elevated temperatures decreases for increased fire exposure severity. For a char depth of 12 mm (0.5 in.), the observed depth of elevated temperatures decreased from 36 mm to 30 mm (1.4 in. to 1.2 in.) when the level of a constant heat flux exposure was increased from

15 kW/m^2 to 50 kW/m^2 (White and Tran 1996), For a char depth of 6 mm (0.2 in.), the depths of elevated temperature were 34 and 25 mm (1.3 and 1.0 in.) for the heat flux levels of 15 kW/m^2 and 50 kW/m^2, respectively.

The irreversible effects of elevated temperatures on mechanical properties depend on moisture content, heating medium, temperature, exposure period, and to some extent species and size of the piece involved (Green et al. 1999). Over a period of months, temperatures of 66°C (150°F) can significantly reduce modulus of rupture (MOR). Graphs of the permanent effect of oven heating for periods up to 200 days on MOR and modulus of elasticity (MOE) can be found in the Wood Handbook (Green et al. 1999). After 50 days of oven heating at 115°C (240°F), MOR at room temperature was approximately 90 percent of the unheated controls. For samples heated at 135°C (275°F), MOR at room temperature was approximately 62 percent of the unheated controls after 50 days. Permanent losses in strength occurred more rapidly with heating temperatures of 155°C (310°F) and 175°C (350°F). Elevated temperatures below charring temperature appear to have little effect on MOE.

Using the data of Knudson and Schniewind (1975) and Schaffer (1973), Schaffer (1977, 1982a, 1982b) developed graphs of temperature effects on tensile (**Fig. 4.7**) and compressive (**Fig. 4.8**) strength. The data illustrates the reduced impact that temperature has on the residual strength properties once the wood has cooled to room temperature and has been reconditioned back to 12 percent moisture content. At a depth of only 8 mm (0.3 in.) beneath the char layer, the temperature has dropped to 200°C (**Fig. 4.6**). At 200°C, residual strength properties still exceed 80 percent of the initial room temperature values (**Figs. 4.7 and 4.8**). Additional information on the effects of temperature and moisture content on strength properties of wood are provided by Schaffer (1982a). Gerhards (1982), Green et al. (1999), and Buchanan (2001). During an actual fire, the residual capacity of the wood member is affected by steam generated within the member (Buchanan 2001) and zones of elevated moisture content (White and Schaffer 1980). Schaffer (1982a) concluded his discussion of the proper-

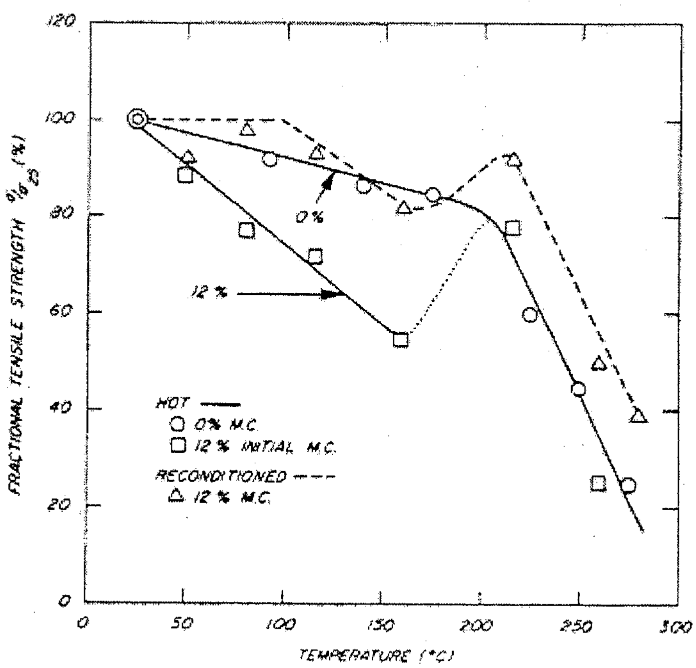


Figure 4.7.—*Fractional tensile strength as function of temperature (Schaffer 1977, 1982b, 1984).*

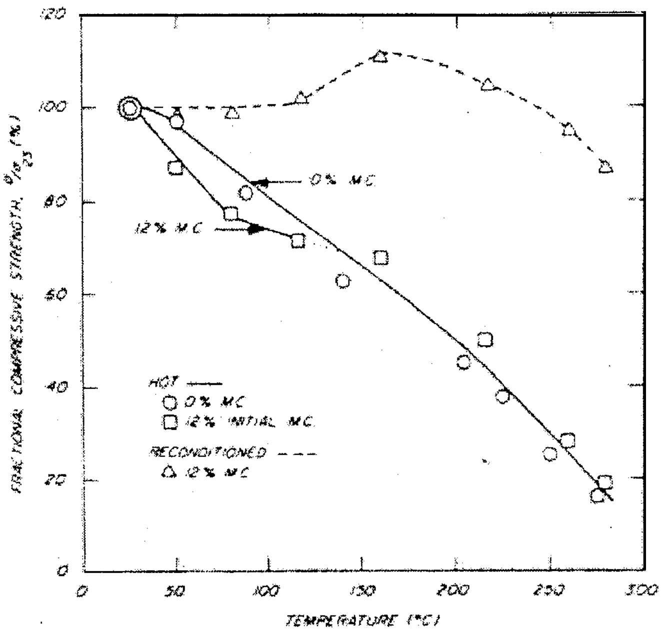


Figure 4.8.—*Fractional compressive strength as function of temperature (Schaller 1982a, 1982b).*

ties of timbers exposed to fire by noting that because of the short time that wood just beyond the charline has been at its maximum temperature, the overall strength loss in heavy sections will be small and the residual load-carrying capacity will be closely approximated by using the initial strength properties of the uncharred residual cross section as a base.

Thus, the steep temperature gradient allows us to easily estimate the residual load capacity of the member by reducing the residual cross section of the uncharred section by an additional amount to improve the safety margins of our calculations. In general, fire endurance design of wood members is referred to as the reduced or effective cross-section method (**Fig. 4.5**). A notional char depth defines the effective cross section for calculation purposes. In their model of a large glued-laminated member in a fire, Schaffer et al. (1986) calculated a reduction of 8 mm (0.3 in.) for tensile strength loss. In the new U.S. procedure for fire endurance design of wood members, the reduction for load capacity calculations is an additional 20 percent of the actual depth of charring (AF&PA 2003). For a 1-hour fire-resistance test, this calculates to 8 mm (0.3 in.) (char depth of 38 mm (1.5 in.)). The AF&PA's American Wood Council procedure also uses a non-linear char rate (White and Nordheim 1992). In calculating the ability of a member to maintain a specified load in a fire test, the reduced cross-sectional area is multiplied by ultimate strength properties. In calculating the residual load capacity of a member after a fire, the reduced cross section is multiplied by the allowable stresses as in normal allowable stress design (AF&PA 2001).

In his discussion of the assessment and repair of fire-damaged buildings, Buchanan (2001) notes that residual wood under the charred layer of heavy timber structural members can be assumed to have full strength. He continues with the comment that the size of the residual cross section can be determined by scraping away the charred layer and any wood which is significantly discolored. Williamson (1982a) recommends that the amount of char/wood that should be removed by sandblasting or other means should be equal to the char layer plus approximately 6 mm (0.2.5 in.) or less of the wood below the char-wood interface. The exposed surface should then have the appearance of normal wood. Williamson (1982a) makes a distinction between design capacities controlled by compression strength or stiffness and those controlled by tensile strength. In the compression case, the removal of the additional 6 mm (0.25 in.) of wood is sufficient to use the residual cross section in the design calculations without any additional adjustment. For the case of tensile design calculations, Williamson (1982a) recommends an additional adjustment beyond the removal of 6 mm (0.25 in.) of wood. In calculations of the residual tensile strength of the member) the basic allowable design stress values should be reduced by 10 percent. An alternative is to take a reduction of 16 mm (0.625 in.) of wood beyond the char-wood interface and use 100 percent of the basic allowable design stress values.

Removal or degradation of any wood from a structural member will likely require regrading of the member to determine the proper allowable properties to be used in calculations of residual load capacity. The grade of the structural member may have changed due to the loss of the outer layer of wood. Calculation of residual load capacity must take into account structural grade variation of individual components within a composite structural wood member. This is very important for charred glued-laminated (glulam) structural members. Glulam members are normally manufactured with a graded lay-up that has higher grade materials at the outer laminates and lower grade materials in the core. In particular, the charred bottom laminate may have been a high-grade tension laminate that significantly impacts the bending strength of the member. Examples of calculations for fire-damaged glulam members are provided by Williamson (1982a). Williamson (1982b) also discusses the rehabilitation of fire-damaged heavy timbers at the Filene Center for Performing Arts at Wolftrap Farm, Virginia. The structure was damaged due to a fire while the facility was under construction in 1971.

Light-Frame Members

As discussed, most information on fire-damaged wood focuses on evaluation of large timber members. Evaluation of residual load capacity of structural elements in light-frame construction does not allow some of the assumptions of the previous analysis such as direct fire exposure and semi-infinite slab.

Wood structural members in light-frame construction are generally covered by a membrane of gypsum board. Gypsum board provides very effective fire protection. Gypsum is primarily hydrated calcium sulfate. Bound water within the gypsum board delays the rise of the temperature at the wood-gypsum board interface above 100°C (212°F) for a significant period of time. The chemically bound water is released as steam during this calcination process. Gypsum board loses its integrity or cohesion after exposure to fire (Cramer et al. 2003). The integrity of the gypsum board can be examined by using a sharp blade or by removing samples for more careful examination. Spiszman (1994) suggests grinding a sample of the gypsum (minus the paper) and moistening it with water to a paste-like material. If, after two hours, the sample is hard, similar to plaster of Paris, it should be considered heat damaged. As with fire-damaged wood, similar materials in areas not involved in the fire provide a performance level for comparison. A rule of thumb is that gypsum board may be assumed to retain its integrity as long as the paper envelope has not charred (King 2002). The cross section of the gypsum board can be examined for visual evidence of the progression of calcination through the gypsum board. Where there is evidence of fire damage, the gypsum board may need to be removed so that structural wood members can be examined. Charring of wood is more likely to occur at the joints between sheets of gypsum board. Due to the protection provided to the sides of the wood members, the damage to structural members in assemblies with cavity insulation may be limited.

In light-frame construction, significantly charred members are generally removed (Steven Winters Associates, Inc 1999). Application of the guidelines discussed above to light-frame construction results in inadequate load capacity with even a small amount of charring. However, many light-frame members in an actual fire suffer only smoke damage or very superficial charring. Given the high temperature of a fire and the low temperature for wood char (300°C (550°F)), superficial charring reflects very brief exposure to a fire. As previously discussed, the depth of elevated temperatures is less for initially smaller depths of charring. Charring is much more rapid during initial charring. As the thickness of the insulative char layer increases, the progression of charring is slowed Once the temperature at the center of the light-frame member starts to increase, the temperature profile shown in **Figure 4.6** is not valid and temperatures will increase more rapidly. King (2002) states that structural repair of fire-damaged framing is often not required if the char depth is less than 6 mm (0.2 in.). He also notes that treatment of any significant loss of surface should have approval of a local building inspector or a qualified structural engineer. Other rules of thumb that have been recommended for lumber in trusses include 1) no charring, 2) charring of up to 10 percent of the cross section, and 3) charring depth up to 1.6 mm (1/16 in.) (WTCA 2003). Engineering judgement on whether a member needs to be replaced includes considering the importance of the member to the structural integrity of the building and the need for a conservative approach.

Light-frame construction contains numerous building cavities. When fire damage is not extensive, heat, smoke, and water damage can occur within the building cavities. In a cavity, fire-generated heat damage would involve components with higher sensitivities than the surrounding materials (King 2002). In addition to the cavities of the structural components, there are also many cavities associated with the routing of the building's utilities.

Testing

Unlike wood damaged by decay, little work has been done on suitable methods for field testing fire-damaged wood for residual load capacity. Some potential options are those suggested for field testing fire-retardant-treated (FRT) plywood for possible thermal degradation (NAHB National Research Center 1990). Prolonged elevated temperatures, associated with roof applications, have resulted in degradation of plywood treated with some formulations of fire-retardant treatments. The thermal degradation of the plywood was similar to degradation of wood in a fire. The options identified by the National Association of Home Builders (NAHB) for possible degraded FRT plywood induded:

1) concentrated proof load,
2) removal of small samples for laboratory mechanical testing,
3) screw withdrawal test,
4) chemical analysis for chemical compositions of the wood such as hemicelluloses, and
5) spectral analysis for end products of degradation.

Options 1) and 2) are destructive.

In the case of options 3), 4), and 5), further research is needed to identify and document any appropriate correlations and methodologies for fire-damaged wood. Since general correlations are likely to lack adequate precision to establish actual property values, these options are more likely to be fruitful when they are used to compare similar members in the fire-damaged building that have obvious degrees of degradation or residual load capacity. Thus, they may be more useful in evaluating fire damage in light-frame construction.

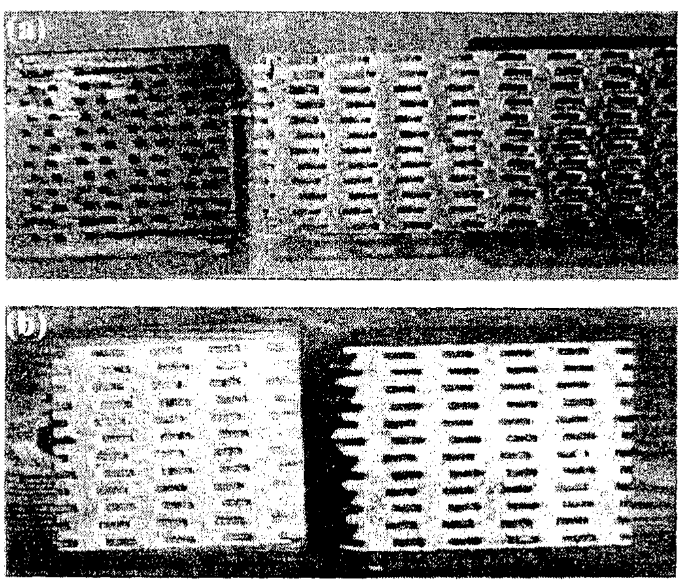
Application of a screw-withdrawal test to the FRT plywood situation was investigated by Winandy et al. (1998). In their study, the variability and reproducibility of 8-mm (5/16-in.) screw insertion was compared to that for 16-mm (5/8-in.) screw insertion in 16-mm (5/8-in.) plywood. The shorter depth measurements were observed to have higher coefficients of variation. In many instances, the load cell resolution of the apparatus exceeded 25 percent of the measured value compared with less than 10 percent for the 16-mill (5/8-in.) screw. While there may have been some gradient in the FRT-plywood degradation through the thickness of the plywood, the application of the method to fire-damaged wood would need to be able to identify degradation prirnarily near the surface of the uncharred wood.

Recent research has been done on modeling strength loss in wood by chemical composition (Winandy and Lebow 2001). Potentially, an increment borer could be used to extract wood samples for chemical or spectral analysis.

Connections

All connections will require detailed inspection to assess their load-bearing capacity. in his discussion of large fire-damaged timbers, Williamson (1982a) notes that the effect of fire on the strength of any connection is very difficult to determine without a thorough investigation of the affected connection, since the amount of damage is dependent on the quantity of metal and the surface contact of metal with fire along with other factors. There may also be possible chemical damage from the corrosive effects of fire residues. Metal roof supports, ceilings, and other structural members are vulnerable to long-term acid attack from fire residues (King 2002). Exposed metal connections provide a means for heat conduction into the wood (Fuller et al. 1992),

It is the degradation of the wood beneath a metal plate connection that results in its failure (**Fig. 4.9a**). In a situation when heating is strictly via radiation, the metal plate may actually initially protect the wood beneath the plate from charring as much as the adjacent wood (**Fig. 4.9b**). The test specimens shown in **Figure 4.9** are from a project to develop a fire endurance model for metal-plate-connected wood trusses (White et al. 1993, Shrestha et al. 1995). If there is damage to the plate area, the plate is discolored, or there is charring under the plate, it is recommended that the connection be considered ineffective (WTCA 2003).



Figures 4.9.—*(a) Test specimens of metal plate connections illustrating charred wood failure beneath the plate, and (b) metal plate failure of plate with uncharred wood beneath the plate.*

Smoke Damage

The subjects of smoke damage and control of odor are not within the scope of this manual. The impact of fire residues on wood framing is confined to appearance and odor (King 2002). Except for possible corrosive effects on metal fasteners, smoke and other fire residues do not affect the load capacity of the wood member. The National Institute or Disaster Restoration (NIDR) provides guidelines based on current practice in restoration technology (King 2002), The institute is associated with the Association of Specialists in Cleansing and Restoration (www.ascr.org). Actions for addressing smoke damage are also discussed in an article by the Chicora Foundation (2003).

Fire odors should be identified and removed before any application of sealers, paints, or other finishes since the masking effects of such products are temporary (King 2002). The presence of fire acids, visible fire residues, and odor need to be addressed. The NIDR's *Guidelines for Fire and Smoke Repair* (King 2002) provides information on methods for removal of fire residues, neutralizing acid residues, removing fire odors, and the use of sealing and encapsulation. Structural members restored after fire damage should retain no char or untreated fire residues even when they are covered with new framing or other interior finishes (King 2002).

Repairs

Once the load capacities of the fire-damaged members are determined, potential repairs can be identified. When blasting is required, various media can be used including sand, ground corn cob, and baking soda. Once char and other fire residues have been removed, wood surfaces can be treated for residual odors and sealers can be applied.

Information on rehabilitation of damaged structures is available in the nine volume series of the PATH program (www.pathnet.org) of the U.S. Department of Housing and Urban Development known as *The Rehab Guide.* Information on moisture damage will help address water damage due to fire suppression efforts. With the high level of concern about mold damage, any moisture damage associated with fire suppression also needs to be addressed. Restoration of wood floors is discussed by King (2002).

In the case of partially fire-damaged wood, repairs often consist of reinforcing the original damaged member by attaching a supplemental piece of wood to it. This action is referred to as "sistering." The effect of fire on epoxy-repaired timber is discussed by Avent and Issa (1984). They found the two epoxies they tested to be sensitive to heat at a relatively low temperature (66° to 93°C (150° to 200°F)). Buchanan and Barber (1994) found the two epoxies they tested lost strength rapidly at 50°C (122°F). Epoxy joints should be protected by a thick outer wood layer or other protective material such as gypsum board. Available information indicates that adhesives (phenol, resorcinol, and melamine) normally used in the manufacture of structural wood composites have a fire performance equivalent of solid wood. Schaffer (1968) found that separation did not occur at either phenol-resorinol or melamine gluelines in either charred or noncharred laminates during fire exposure.

Any repairs should also include the consideration of design changes or additional protection to reduce the likelihood of future fire damage. Schaffer (1982c) discusses designing to avoid problems with fire. Additional information can be found in the *Wood Handbook* (White and Dietenberger 1999). Repairs must comply with appropriate building code requirements.

Concluding Remarks

Often, the end product of the reaction of wood to fire is an outer char layer and a cooler inner core of solid wood. In the case of many fires, there is a clear demarcation between the char layer and the relatively undamaged residual wood. With appropriate analysis, treatment, and repairs, the fire-damaged wood members can be restored instead of being replaced (**Fig. 4.10**).

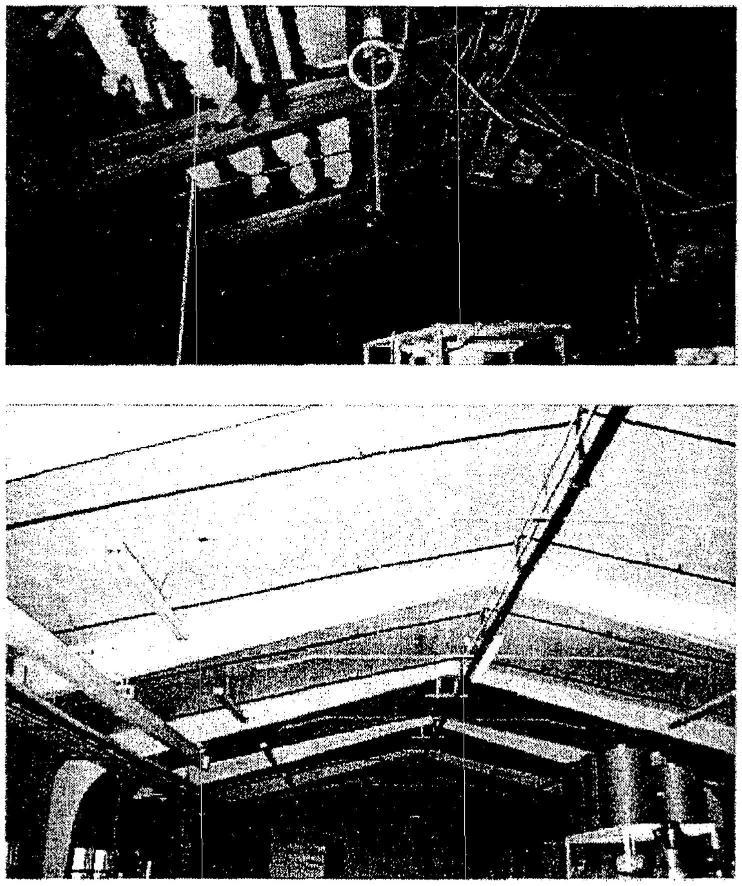


Figure 4.10.—*Post-fire (top) and post-repair (bottom) of Building 2 at the Forest Products Laboratory.*

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Wood and Timber Condition Assessment Manual

Robert J. Ross
Project Leader
USDA Forest Service
Forest Products Laboratory
Madison, WI

Brian K. Brashaw
Program Director
Natural Resources Research Institute
University of Minnesota Duluth
Duluth, MN

Xiping Wang
Senior Research Associate
Natural Resources Research Institute
University of Minnesota Duluth
Duluth, MN

Robert H. White
Project Leader
USDA Forest Service
Forest Products Laboratory
Madison, WI

Roy F. P.ellerin
Professor Emeritus
Washington State University
Pullman, WA

Forest Products Society
Madison, WI

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