Chapter 6

FIRE DAMAGE OF WOOD STRUCTURES

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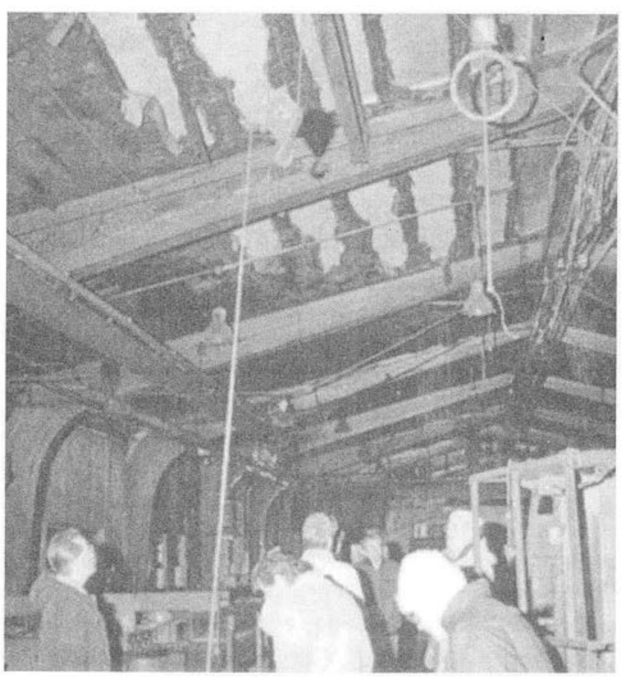
INTRODUCTION

Depending on the severity, fire damage can compromise the structural integrity of wood structures such as buildings or residences. Fire damage of wood structures can incorporate several models that address (1) the type, cause, and spread of the fire, (2) the thermal gradients and fire-resistance ratings, and (3) the residual load capacity (Figure 6.1). If there is a danger of local collapse, immediate concerns about the stability of free-standing residual parts of a fire-damaged building will need to be addressed very quickly [1]. Assuming that the structural fire is contained, then under certain circumstances time becomes less of an issue.

The investigator should employ engineering judgment to identify those in-service members that are to be replaced, repaired, or can remain in-service as they are. Such judgment will likely be based on the visual inspection of damaged members, connections, and any protective membranes. In light-frame construction, wood assemblies are typically shielded from flames and heat by gypsum board and insulation; these greatly increase the amount of time required for the onset of charring. Potential methods for nondestructive evaluation of structural properties of a fire-damaged wood member are described below.

From start to finish, wood construction incorporates numerous wood products into a number of primary and secondary structural applications. Wood is inherently variable, and there are a number of factors that contribute to the performance of wood-based materials. Grading procedures account for the underlying factors of wood strength such as specific gravity, slope of grain, and the presence of knots. Grading procedures include visual grading criteria; nondestructive measurement such as flat-wise bending, stiffness, or density; or a combination thereof [2]. For purposes related to post-fire assessments where the tabulated allowable design stresses for the grade are employed, it is recommended that the wood members be re-graded after the char is completely removed. The charring of the wood member is similar to ripping the wood member with a saw in terms of its impact on the mechanical properties and grade of the member. Re-grading procedures take into account the impact of residual dimensions on the applicable grading rules for the reduced dimension as well as the altered relative locations of strength-reducing characteristics (such as knots) in the cross-section. Current accredited grading agencies are listed in a document of the American Lumber Standard Committee [3]. Once the species of lumber or timber is identified, various agencies that supervise the grading of the specific species (or species group) can be contacted to locate a qualified grader for the re-grading work.



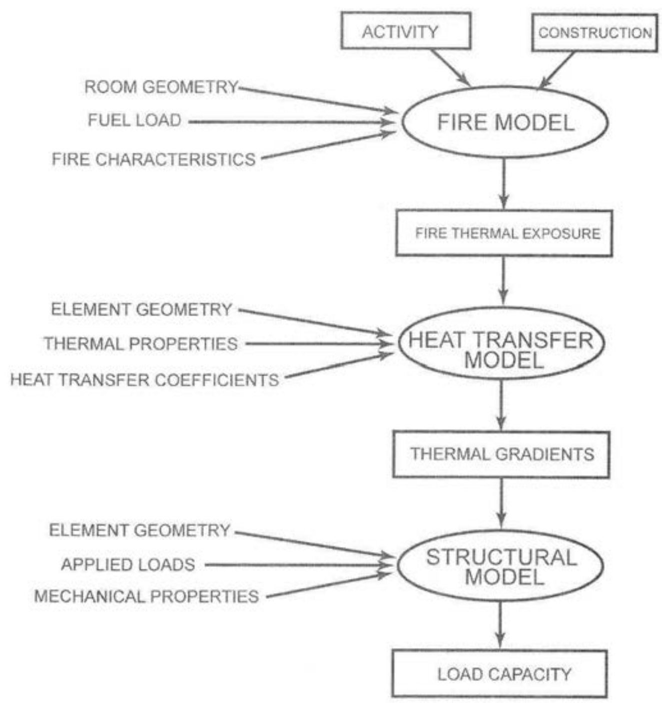


Figure 6.1
A fire-damaged building at the US Forest Products Laboratory and a flowchart [1] for modeling fire-damaged wood members in a structural fire

The American Forest & Paper Association (AF&PA) publishes allowable design stresses that are category specific and segregated according to the species (or species group) of material and commercial grade. These tabulated design values are recognized by the building codes and can be adjusted to account for a host of factors that depend on the size, application, load combination, and member spacing, to name a few [4]. As a matter of procedure, determining the residual capacity of fire-damaged wood members should also be considered to be category specific. Wood products such as dimension lumber (2 to 4 inches thick by **2** inches and wider) and similar sized composite products fall into one category. Timbers (5 by 5 inches and larger) and glued-laminated beams should be considered in another category. The two categories reflect the different assumptions that will need to be made in the assessment of the residual structural capacities of the wood products.

FIRE DAMAGE AND THERMAL BEHAVIOR OF WOOD

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 sources are consumed. The fire exposure of a standard fire-resistance test, such as ASTM E 119 [5], 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 out the door in the standard room-corner test. Information gathered in a NFPA 921 [6] investigation will help establish likely maximum temperatures in various locations.

When heated to high temperatures, wood undergoes thermal degradation to char and volatile gases. Products such as plywood and particleboard have ignition properties very similar to solid wood, so the solid-wood results will generally be applicable to them [7]. Piloted ignition at heat fluxes sufficient to cause a direct-flaming ignition normally occurs at surface temperatures of 300 to 365 °C [7]. Piloted ignition occurs when there is an external flame or spark to ignite the combustible gases generated by the thermal degradation of the wood.

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 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 a cool interior (Figure **6.2**). These zones of degradation reflect the temperature profile through the cross-section.

For the fire exposure of the standard fire test used to determine the fire-resistance ratings of structural members, there is considerable data on the charring rate and temperature gradients of the remaining uncharred wood in a semi-infinite wood slab [8, 9, 10]. For such exposures, it is generally assumed that the temperature at the base of the char layer is 300°C. The thickness of the wood layer with elevated temperature beneath the base of the char layer is approximately 38 mm, and the temperature profile can be approximated by a parabolic curve [11]. Beneath this layer is the wood unaffected by the fire. These equations and

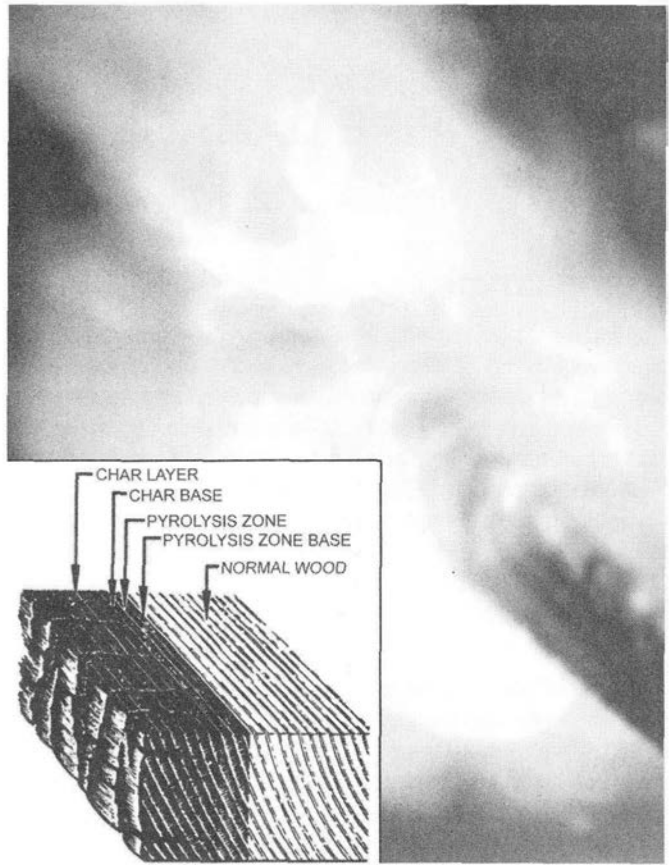


Figure 6.2
Degradation zones in a charred piece of wood [8]

data for calculating char rates and temperature gradients are valid when the member is thick enough to be considered a semi-infinite slab. However, once the temperature has risen above the initial temperature at the center of a structural member or on the back side of a panel product, the charring rate increases, and the temperature profile changes. Except for fires of short duration, this will often quickly be the case for panel products and the dimension lumber of light-frame construction. This phenomenon affects the thermal and structural behavior alike and influences the assumptions that can be made in the post-fire assessment.

As just discussed, most available data on the structural performance of wood in a fire is based on research using the standard fire-resistance test. For the post-fire assessment, the investigator should consider the exposure of the structural wood members to elevated temperatures during the decay period of fire development. While the temperatures are lower during the decay period, the duration of the 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 a prolonged cooling, the surface temperatures will decline while interior layer temperature will increase. Tests have indicated that this increase in the temperature in the interior of the wood member, due to redistribution of the 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 observations of damage at the fire scene will be less helpful in establishing the intensity and duration of the exposure during this period.

Temperatures below a threshold of 300°C can still have a demonstrated detrimental effect on wood. The National Design Specification for Wood Construction [4] indicates that properties of wood heated up to 66°C (150°F) for brief periods will essentially return to their original levels when the wood is cooled. However, prolonged exposure to temperatures above 66° C may result in permanent loss in properties [12]. It is also worth noting that over a period of months even temperatures of 66°C (150°F) can significantly reduce the strength of the wood, although elevated temperatures below the charring temperatures appear to have little effect on the stiffness. This is discussed in greater detail in the next section and in publications [1, 8, 13].

STRUCTURAL BEHAVIOR AND RESIDUAL PROPERTIES OF WOOD

Historically, the calculation of structural behavior has been made more difficult than the calculation of thermal behavior because of the poor knowledge of mechanical properties of wood at elevated temperatures [1]. Prior to a fire being extinguished, the residual capacity of the wood member is affected by steam generated within the member [1] and zones of elevated moisture content [14]. Once the fire has been extinguished, data presented by Knudson and Schniewind [15] and Schaffer [8, 13, 16, 17, 18] indicate a reduced impact of temperature on the residual strength properties once the wood has cooled to room temperature and reconditioned to normal moisture content. The moisture content is an underlying factor of wood strength that can readily be verified by the use of a moisture meter during a post-fire investigation. However, immediately following a fire the moisture content of charred members is likely to fall below 6.5 percent, a value associated with the lower limit of most moisture meters. Generally speaking, a 1 percent change in moisture content can affect wood strength properties by as much as 2 to 6 percent [19]. Kretschmann [20] and Gerhards [21] provide additional information on temperature and moisture content effects on the strength properties of wood in general.

In terms of post-fire investigations, ongoing research will continue to increase our knowledge of the irreversible behavior of wood materials after they have been exposed to elevated temperatures. Based on what we have learned to date, these irreversible effects are dependent on moisture content, heating medium, temperature, exposure period, and, to some extent, species and size of the piece involved [20]. Specific to the structural behavior of individual wood members, residual properties that address both the apparent modulus of elasticity (E_r) and the modulus of rupture (S_r) are likely to be of value. The E_r indicates the stiffness of a particular material; in this case, wood. Both properties are recognized indicators of wood's strength. Wood-framed floors behave similarly to wood-framed walls in that structural failure occurs when charring of the timber joists causes significant loss of load capacity [1]. When determining residual properties, the engineer must consider the importance of a member in relation to the structural integrity of the building.

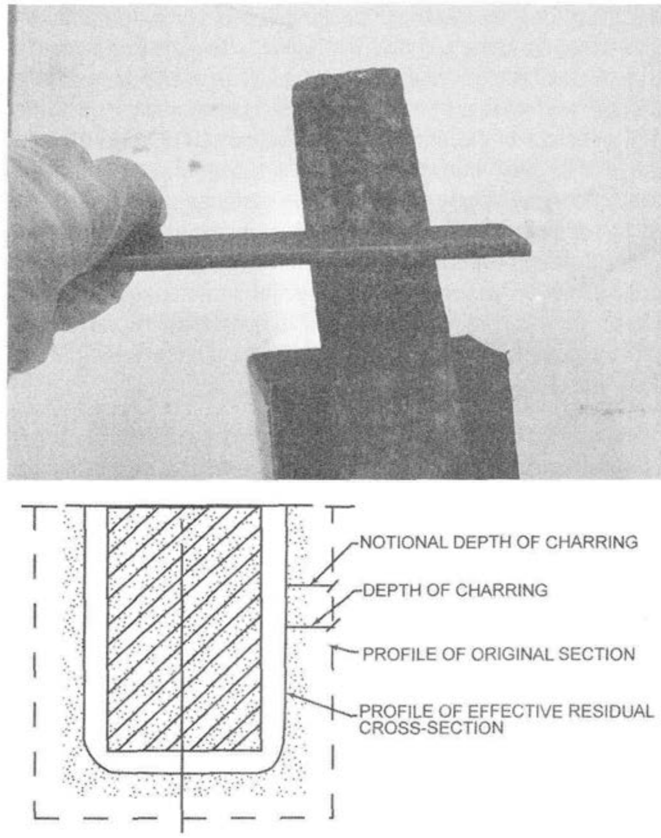


Figure 6.3
Profile of a charred piece of wood [inset (22)]

The char layer can be easily scraped off a member that has been charred (Figure 6.3). 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. At a depth of only 8 mm (0.3 in.) beneath the char layer, the temperature is about 200°C. At 200°C, the residual strength properties still exceed 80 percent of the initial room temperature values. Members themselves that have only visual smoke damage or slight browning of the surface also have significant residual load capacity [22].

Calculations based on reduced cross sections are often used to determine the residual load-bearing capacity of large members such as timbers (five inches or greater in the least dimension). The reduced cross section is used to account for the actual section reduction due to charring and the effect of elevated temperatures on the residual wood cross section. The results of charring, temperature, and moisture gradients below the char layer reduce the strength and increase the plasticity of the wood [1]. The reduced cross section is used in normal room temperature load calculations based on appropriate grading of the member. These models were developed to predict or calculate the fire-resistance ratings of large, exposed wood members. The supporting data are from standard fire-resistance tests typically of one hour duration. One such calculation procedure is discussed in the National Design Specification for Wood Construction (NDS). It obtains the reduced cross section by increasing the reduction due to charring by 20 percent. According to the NDS-2005 *Commentary* [23], the factor 1.2 is used in the calculations to account for rounding at the corners and reduction of strength and stiffness of the heated zone. According to Schaffer [17], because of the short time that wood just beyond the char line is at its maximum temperature, the overall strength loss in heavy sections will be small, and the residual load-carrying capacity will be closely approximated if the investigator uses the initial strength properties of the un-charred residual cross section as a base. Any assessment of a glued laminated beam must take into account the grade of the individual laminates. This is particularly the case for beams with a high-grade tension laminate that likely was subjected to the most charring.

The application of the reduced section methodology to dimension lumber and similar sized composite products normally presents two problems. Dimensional lumber and similarly sized composite wood products quickly do not meet the criterion of a semi-infinite slab that is one of the assumptions of the supporting test data. Also, the reduced section will likely have inadequate structural capacity whenever there is any significant amount of charring. Some codes ignore any reduction in wood strength below the char, and this practice can lead to unsafe results for small cross sections less than 100 mm (3.94 in.) thick [1]. To this end, limited work on the flexural properties of fire-damaged specimens from the materials common to light-frame construction has been performed.

Generally speaking, the results of four-sided fire exposure on small clear (1½-inch by 1½-inch by 23-inch) specimens indicate that when depth and width dimensions in the fire-damaged cross sections approach ¼ inch, the following degradation in flexural properties is noted: laminated veneer lumber (LVL) specimens retain an average stiffness of 72.5 percent (E_f), post charring; machine stress rated (MSR) specimens retain an average stiffness of 83 percent, post charring; and laminated strand lumber (LSL) specimens retained an average stiffness of 85.5 percent, post charring. In terms of residual strength (MOR), results indicate that the 1.9E LVL specimens retain an average residual strength of 79 percent, post charring. The 2250f-1.9E MSR specimens retain an average residual strength of 73.9 percent, and the 1.7E LSL specimens retain an average residual strength of 64.4 percent [24]. The data are specific to the fire exposure and the small-clear-specimens tested and are intended only to show the impact of such exposure.

In light-frame construction, significantly charred members are generally replaced. Qualitatively speaking, individual wood members used in light-frame construction are typically taken out of service when fire damage reduces the total dimension of a member by approximately ¼ inch or more in depth, due to the lack of established residual strength properties. It appears that a common practice is to not require structural repair of fire-damaged framing if the depth of char is less than 6 mm (¼ inch), and the residual sections are determined to be adequate by a design professional. Similar statements for fire-damaged roof trusses that are expected to remain in service are typically more conservative. In some cases, truss members may be stressed to nearly 100 percent of the allowable stress at the design stage, and therefore any loss of section would overstress the fire-exposed member. Here, the rule of thumb states that if there is no charring then there will be less than a 10 percent reduction from the original cross section dimensions or depth-wise reductions less than $^{1}/_{16}$ inch. Any inspector's assessment of damage of light-frame construction must consider the location and structural requirements of the member(s) and their expected loads in terms of the allowable stress of the member(s).

The most difficult question in post-fire assessment of wood structures is the assessment of light-frame construction in situations when there is little evidence of any charring or only surface char. An example of such a situation is afire in the living space in which heated air is exhausted through the roof and its structural members. Based on methodologies used for other types of damage assessments, there are direct methods that may provide evidence of damage to the residual structural behavior of light frame members. These will be discussed in the example of "Direct Determination of Dimensional Lumber and Composite Wood Products." By comparing results for the members in question with results for similar members away from the fire, it may be possible for the engineer to obtain evidence of either damage or the lack thereof. Due to the variability in structural properties of individual members and the importance of knots and other characteristics to the grade of an individual piece of lumber, the nondestructive direct determination of actual degree of loss in structural load capacity of an individual un-charred member, i.e., re-grading, is difficult.

First an example of the determination of fire damage to timbers.

DIRECT DETERMINATION OF FIRE-DAMAGED TIMBERS

This example assumes heavy timber beams are exposed to fire and charred to some depth before the fire is extinguished. After such a fire exposure, inspection professionals will need to determine if the charred heavy timbers are to be replaced, repaired, or can remain as is in order to satisfy the provisions of the current applicable building code for the use and occupancy. The following steps are a logical sequence that could be employed by a design professional to evaluate fire-damaged timbers.

Step 1. Inspection to Estimate Timber Char-free Nominal Size

After inspection of all affected timbers, the fire-damaged timber floor beams are about 8-inch by 12-inch (nominal) surfaced-four-sides (S4S) southern pine, and none of the timbers have grade marks. Varying degrees of degradation are present, and the most severely charred members are identified. At this point of the investigation, only the estimated char depth on the three exposed faces of the timbers needs to be determined. This step can be accomplished as the inspector carefully scrapes a small area of char on the three exposed sides to measure the char-free section dimensions. Sanding the area below the removed char isn't necessary at this stage of the investigation. For the beams examined, char depths are recorded as well as measurements on similar timbers with minor char that reveal that the timbers were probably manufactured as "unseasoned" 8-inch by 12-inch timbers at the time of construction, and the residual dimensions reflect about a ½-inch reduction for each of the three exposed surfaces in comparison to smoke-damaged members (Figure 6.4).

Figure 6.4
Fire-damaged timber floor beam

Step 2. Feasibility Analysis

The investigator conducts a feasibility analysis to determine if the fire-damaged beams can remain in service "as is" and be code-conforming based on the current applicable building code for the jurisdiction. This analysis requires that all loads be defined and checks be performed as given by the current applicable building code for the jurisdiction.

To determine the likelihood that the charred timbers may b e adequate once they are graded by a qualified lumber grader, section properties for a new No. 2 Southern Pine 8-inch by 12-inch timber can be artificially reduced on the three fire-exposed sides based on the char depths measured in Step 1 plus a correction factor for a damaged layer under the char. The design professional can use these dimensions as a basis for determining if the fire-damaged beams have a reasonable chance of being adequate under the current applicable code and load requirements.

In the NDS calculation of the fire-resistance rating of an unexposed large wood member, a factor of 1.2 is used in the calculations to account for rounding at the corners and the reduction of strength and stiffness of the heated zone. For a one-hour standard fire-resistance exposure, the resulting reduction is similar to other recommendations for fixed reductions (e.g., 0.25 inch) in the cross-sectional dimensions [22]. When applying the NDS fire-resistance rating procedure in a post-fire application, the engineer should multiply the measured char depths by 1.2 before subtracting it from the estimated original "dry" dimensions.

Accordingly for a preliminary structural analysis, the investigator can calculate the post-fire section properties for a beam exposed on three sides and charred ½ inch deep on three sides by applying the 1.2 factor given in NDS Section 16.2.1 to an assumed char depth as follows:

B^* = Theoretical analysis width = 7.5" – (2) × (1.2) × (0.5") = 6/3 in.
D^* = Theoretical analysis depth = 11/5" – 1.2× (0.5") = 10.9 in.

At this point, the inspector can use the section properties (B^* and D^*) for a preliminary analysis to decide to go forward with the investigation by having the species (or species group) confirmed and by having all timbers visually-stress-rated (VSR).

Step 3. In-depth Structural Evaluation

Assuming the results of the preliminary analyses are favorable to the likelihood of the timbers being "saved" or repaired, the next step for the engineer is to remove all char from the sides of each timber and to record the char depth based on original dimensions. Following the char removal, each face must be sanded by an additional 20 percent of this reduced dimention (additional sanding may be required for good appearance). The purpose of this step is to expose wood fiber (not thermally damaged from heating) to the grader as well as to reveal the member size free of char and thermally-damaged fiber. These steps are necessary because grade rules are based on member size of virgin wood fiber and the characteristics (such as knots) of the outer zones of a member that greatly impact the visual stress-rating result.

The VSR grading process, performed on site by a grading supervisor, should include certification and documentation of the actual grades of all structural timbers in the project. The VSR-type grading requires that the grader view all faces and at least one end. The grading supervisor may require that the flooring be removed and one end be visible prior to the grading inspection. As such, timber access grading issues should be resolved at the initial contact with the grading professional. Additional consideration may be warrented should the inspection professional note any other adverse conditions such as evidence of insects, decay, and water damage [22]. In particular, decay in structural timbers trumps all other strength and stiffness-reducing factors. Timbers containing decay cannot be relied on to carry future in-service loads. The load history of the timbers is also important. If overloading is suspected, then cumulative damage should be investigated. For background on the impact of decay and damage from overloading, the *USDA Wood Handbook* is recommended [25].

With each side of the beam sanded to at least 20 percent of the measured char depth and the VSR grade determined, the inspector's final calculations should be based on the *measured cross-section* of each timber. Having the species (or species group) and VSR grade established for each timber and the section dimensions recorded, the deign professional can complete the structural engineering work to determine that the timbers are sufficient without repairs or determine how much additional support is needed for a code-conforming structure based on the current applicable building code for the jurisdiction.

DIRECT DETERMINATION OF DIMENSIONAL LUMBER AND COMPOSITE WOOD PRODUCTS

Assuming that the dimensional lumber and/or similar sized products are exposed to fire and allowed to self-extinguish, and assuming the fire is contained, lumber quality can be field verified from neighboring members (Figure 6.5). Although the ignition properties of dimensional lumber and composite materials are very similar to one another, Babrauskus [7] and Kukay and Todd

[24] indicate that the reduced flexural capacities from one material and grade must be considered to be separate from another. Should the inspection professional prefer to forgo the qualitative approach to replacing fire-damaged dimensional lumber (and similar-sized composite products) when residual dimensions decrease by ¼ inch or more for a more direct approach, then he or she should consider the following steps as a logical procedure to be employed under such circumstances.

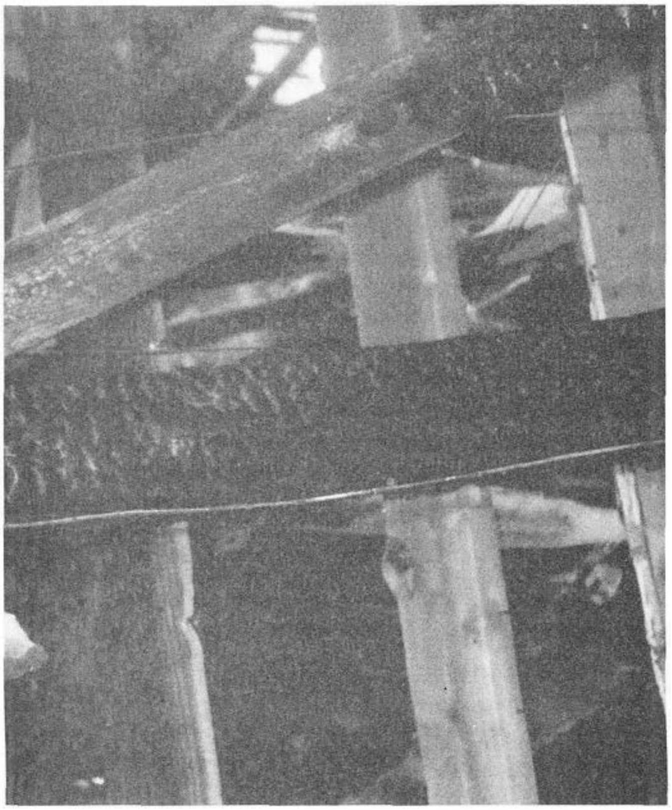


Figure 6.5
Dimensional lumber, identifying degrees of degradation

Step 1. Visual Inspection

The initial step requires that similar members that show obvious degrees of degradation be identified within the structure. This is expected to be the case for contained fires associated with light-frame construction. At this point, the visual inspection will most likely entail the investigator removing small sections of gypsum board, flooring, and suspended ceiling. Appropriate members should be identified as well as stamps or markings that indicate the grade and species for the material(s) under investigation when establishing allowable design properties. The direct methods, presented below, are intended to help quantify obvious differences in residual strength properties but are likely lacking the precision necessary for establishing actual allowable design values.

Step 2. In-depth Field Evaluation

Upon removing the char layer and obtaining residual dimensions from a select number of members, the engineer's next step is to choose one of two techniques. These procedures were among those identified when assessing the residual load-bearing capacity of some fire-retardant plywood used in roof applications for thermal degradation over time [26]. These two techniques are: 1) removal of small samples for laboratory testing, and 2) screw withdrawal tests. Concentrated proof loading is the subject of ongoing research. The National Association of Home Builders (NAHB) [27] provides a complete list of related techniques, which are listed in the *Wood and Timber Condition Assessment Manual* [22]. The underlying goal for the inspector is to quantify these differences as part of a post-fire investigation rather than to establish actual allowable design values.

2A: Static Bending Tests.

This approach requires the inspection professional to remove small specimens from existing members to perform static bending tests. According to ASTM D143 [28], "The need to classify wood species by evaluating the physical and mechanical properties of small clear specimens has always existed" (ASTM International 2009), although large pieces containing defects typical of standard grades of lumber are also tested to develop strength data [19]. Differences in specific gravity, specimen orientation, slope of grain, and moisture content must be accounted for when the investigator compares results from the static bending tests. Information that quantifies these differences can be found in *The Nature of Wood and Wood Products* [19].

ASTM D 5664 [29] specifies a standard procedure for evaluating the effects of fire-retardant treatments and elevated temperatures on the strength properties of fire-retardant-treated lumber. One difficulty in getting estimates of actual property values is the need for a large number of tests due to the variability of wood properties. ASTM D5664 [29] states, "It should be noted that the initial use of at least 30 specimens will usually insure 25 acceptable specimens when testing lower grades of lumber that have lower yields" (ASTM International 2009). This standard specifies a span-to-depth ratio in accordance with dimensions for uncharred specimens of 14:1 (1½ by 1½ by 23 inches that provide 1 inch to either side of the test supports). By comparison, this ratio will increase due to a reduced cross section for the charred specimen cut to be of like span and reflects the fact that the char layer has no residual capacity. All measurements can be taken in accordance with ASTM D 198 [30]. Individual results can be input into appropriate equations to determine both the apparent modulus of elasticity and modulus of rupture. Multiple tests are to be performed or) similar members that show comparable degrees of thermal degradation. Should small clear specimens be preferred to full-sized dimensional lumber, a number of specimens can be removed out of a cross section so the outer zones and inner core of the sample are evaluated.

2B: Screw-withdrawal Tests.

Screw-withdrawal tests can be used to relate the aforementioned residual flexural properties to the maximum extraction loads associated with individual charred members. The maximum extraction load is the peak force required to extract a screw, once inserted. For investigations of this type, three materials that are common to light-frame construction continue to be the focus of ongoing research: machine stress rated lumber, laminated strand lumber, and laminated veneer lumber. Depending on the degree of degradation, the inherent variability of wood may in some instances supersede the reduced capacity of charred members. As with the static bending tests, results obtained from screw-withdrawal tests are best represented when multiple tests, two per specimen, are performed on similar members that have comparable degrees of thermal degradation.

Current practice indicates the use of a digital screw extractor when the engineer is recording the maximum extraction load as a manual force is applied at a uniform rate of increase. From start to finish, each screw extraction is typically administered within 2 to 4 seconds. Digital screw extractors capable of recording the maximum extraction load to the nearest 10 pounds are sufficient. Related research specifies the extraction of $^{8}/_{32}$-inch by 2-inch-long machine screws from $^{5}/_{32}$-inch pilot holes. The machine screws are inserted to consistent depths of 1.5 inches and are measured from the un-charred surface. Because screw-withdrawal resistance is a function of insertion depth, instances may arise where it is necessary for the inspector to place a perforated 0.25-inch thick metal plate between charred members. To limit variability among screw withdrawal tests, only machine screws that are manufactured from similar lots and batches should be used throughout a post-fire investigation. A digital screw extractor is depicted in Figure 6.6.

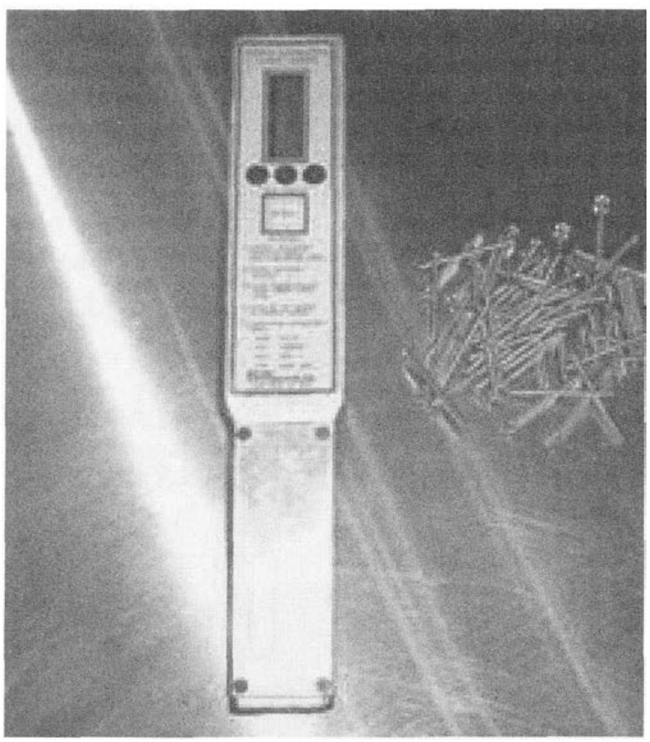


Figure 6.6
Screw-withdrawal test

Advantages that lend themselves to the screw-withdrawal test include the ability of the investigator to perform multiple tests without significantly affecting the residual capacity of individual members. Screw-withdrawal tests can also be performed quickly and for very little cost. Admittedly, some limitations surround screw-withdrawal tests. Post-fire prediction equations for these tests are material and grade specific, data are limited. Any variance in the above-mentioned procedure will invalidate test results. Such variances include the type of machine screw, the size of the pilot hole, the insertion depth of the screw, and the type of ignition. Additional research is needed to address a broader range of materials and grades. In keeping with Winandy et al's [26] findings, "Although the models were shown to acceptably predict bending strength, additional work is needed . . . ." The same can also be said for static bending tests. In instances where the inspection professional is uncomfortable with making such determinations, repairs that do not rely on the residual strength of the charred members may prove to be the most practical course of action.

REPAIR OF FIRE-DAMAGED MEMBERS

Once the engineer determines the load capacities of the fire-damaged members, potential repairs can be identified. When the char and other fire residues have been removed, the 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 of the U.S. Department of Housing and Urban Development (HUD) known as "The Rehab Guide" [31]. 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 needs to be addressed. King [32] extensively discusses building restoration after a fire, including the restoration of wood floors.

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." Avent et al [33] discuss the effect of fire on epoxy-repaired timber. They found two epoxies tested to be sensitive to heat at a relatively low temperature (66 to 93°C [150 to 200°F]). Buchanan and Barber [9] found that 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 materials such as gypsum board. Available information indicates that adhesives (phenol, resorcinol, and melamine) traditionally used in the manufacture of structural wood composites have fire performance equivalent to solid wood. Schaffer [34] found that separation did not occur at a phenol-resorcinol or melamine glue line in either the char or wood during fire exposure. Because of concerns about the fire-resistance performance of some adhesives being used to make finger-jointed lumber, the wood industry established performance qualifications, and the "HRA" markings for end-jointed lumber are interchangeable with solid-sawn lumber in one-hour fire-rated assemblies [35].

Any repairs should also include the consideration of design changes or additional protection to reduce the likelihood of future fire damage. Schaffer [36] discusses designing to avoid problems with fire. Additional information can be found in the *Wood Handbook* [37]. Repairs will need to comply with appropriate building code requirements. Often, the end product of the reaction of wood to fire is an outer char layer and a cooler inner core of solid wood. For 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.

FIRE-DAMAGED CONNECTIONS

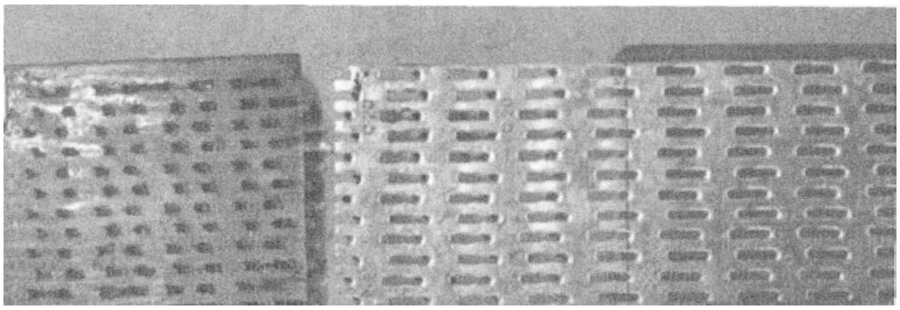
Any connections will require detailed inspection to assess their load bearing capacity. In his discussion of large fire-damaged timbers, Williamson [38] notes that the effects fire has on the strength of any connection is most difficult to determine without a thorough investigation of the affected connection, 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 is also 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 [32]. Exposed metal connections provide a means for heat conduction into the wood [39].

It is the degradation of the wood beneath a metal plate connection that results in its failure (Figure 6.7a). In situations when the heating is strictly via radiation, the metal plate may actually initially protect the wood beneath the metal plate from charring as much as the adjacent wood (Figure 6.7b). The test specimens in Figures 6.7a and 6.7b are from a project to develop a fire-endurance model for metal-plate-connected wood trusses [40, 41]. 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 [42].

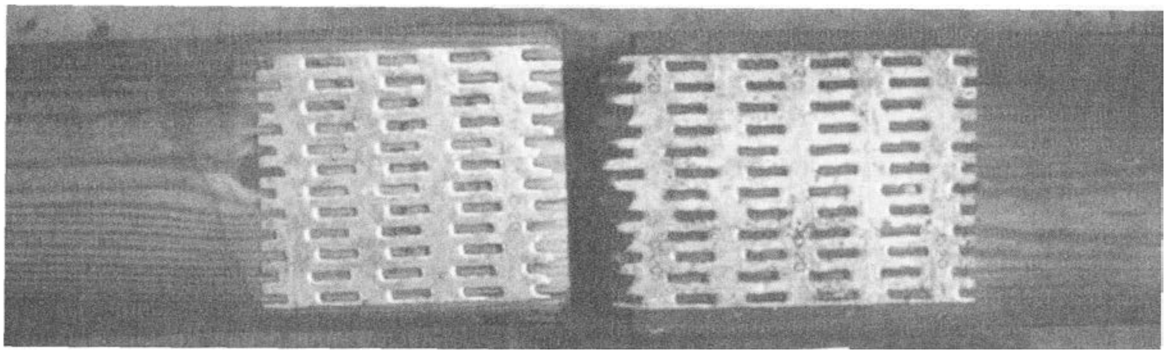
SMOKE DAMAGE

The impact of fire residues on wood framing is confined to appearance and odor [32]. Except for possible corrosive effects on metal fasteners, smoke and other fire residues do not affect the load capacity of the wood member. The Restoration Industry Association, formerly the Association of Specialists in Cleansing and Restoration, publishes the *RIA Guidelines for fire and Smoke Damage Repair;* which provides guidelines based on current practice in restoration technology [43]. The Chicora Foundation article [44] also discusses actions to take to address smoke damage.

Fire odors should be identified and removed before the application of sealers, paints, and other finishes as the masking effects of such products is temporary [32]. The presence of fire acids, visible fire residues, and odor needs to be addressed. The *RIA Guidelines for Fire and Smoke Damage Repair [43]* 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 finish [32].



a) charred wood failure beneath plate



b) failure of metal plate with un-charred wood beneath plate

Figures 6.7a and 6.7b
Test specimens of metal plate connections
(Courtesy of US Forest Products Laboratory)

CONCLUSION

This chapter contains technical background on the inspection, repair, and restoration of wood members and connections. In the final analysis, the structural integrity of fire-exposed members, connections, and systems and building code conformance for future service should be determined by a registered design professional on a case by case basis. Other fire-related issues such as smoke damage and the potential impact of fire damage on the safety and health of building occupants should be evaluated and dealt with by qualified and licensed individuals as required by local, state, and federal regulations.

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