Options for NDE Assessment of Heat and Fire Damaged Wood

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Abstract

Depending on the duration and temperature, heat can adversely affect structural properties of wood. While severe temperatures will result in damage that is visually obvious, damage to wood in terms of structural performance extends to wood that visually appears to be unaffected or only mildly affected. The loss in structural capacity includes both reductions for the duration of the elevated temperature exposure and reductions that are permanent even after normal temperatures are restored. While extensive work has been done to develop techniques for assessing, using nondestructive evaluation (NDE), the residual capacity of wood affected by biological degradation, a comparative small amount of work has been done on NDE of wood exposed to elevated temperatures. NDE techniques for assessing biological degradation include forced vibration, resistance micro-drilling technology, stress wave evaluation, ultrasonic testing, radiography, and near infrared technologies. These techniques and others will be reviewed for their applicability to heat damaged wood.

Keywords: wood, fire, post-fire, damaged wood, NDE, nondestructive evaluation, residual load capacity

Introduction

Heat can adversely affect the structural properties of wood. While severe temperatures will result in damage that is visually obvious, the damage to wood in terms of structural performance extends to wood that visually appears to be unaffected or only mildly affected. The loss in structural capacity includes reductions for duration of the elevated temperature exposure and those that are permanent after normal temperatures are restored. Evaluation methods are needed to assess the extent of damage from exposure to elevated temperatures. Applications for such nondestructive evaluation (NDE) techniques include fire-damaged wood, wood near heat generating utilities or industrial operations, and wood subjected to high temperature processes.

While extensive work has been done on NDE techniques for assessing the residual capacity of wood affected by biological degradation, only limited work has been done on NDE for wood exposed to elevated temperatures. One exception was research done in the late 1980's and early 1990's on NDE for the elevated temperature damage to fire-retardant-treated (FRT) plywood roof sheathings (Ross et al. 1991, Winandy 2001). NDE technologies have also been used in research projects to investigate the damage due to production processes, e.g. heat treatment, and investigate the chemistry of thermal degradation.

Effect of elevated temperatures on wood

From 200 to 300°C, the wood components of hemicelluloses and lignin begin to undergo significant degradation (Browne 1958). Significant depolymerization of the cellulose component of wood occurs between 300 and 350°C. Thermal degradation of the wood to a char residue causes reductions in the density of the wood and the shrinkage of the surface char layer.

The National Design Specification (NDS®) for Wood Construction (American Wood Council 2012) advises that prolonged heating to temperatures above 66°C (150°F) can cause a permanent loss of strength. While days of heating at 66°C can have a permanent effect on mechanical properties, the immediate temperature effect on mechanical properties is reversible for heating periods that are limited to hours at temperatures below 100°C (Kretschmann 2010). In contrast to the immediate impact on strength properties of individual wood members at elevated temperatures, the permanent loss in compressive strength occurs at higher temperatures than a comparative loss in tensile strength (Schaffer 1977). The NDS supplied multipliers that are applied to the tabulated stresses for wood that will experience sustained exposure to temperatures of 100°F to 150°F are more severe (0.5 to 0.8) for bending and compressive stresses than they are for compressive or modulus of elasticity (MOE) (0.9). The irreversible effects of elevated temperatures on mechanical properties depend on moisture content, heating medium, temperature, exposure period, and the species and size of the piece involved (Kretschmann 2010).

Issues in evaluating heat and fire damaged wood

Irreversible effects of elevated temperatures for a given duration are primarily on the strength properties and a considerable smaller effect on the stiffness properties (Kretschmann 2010). Elevated temperature exposure changes the correlation between the MOE and the modulus of rupture (MOR). Thus, a difficulty for NDE based on determining elastic properties is that the property of most interest in terms of safety (i.e. strength properties) are more sensitive to elevated temperature exposure than the properties being measured.

A difficulty in evaluating wood for damage from elevated temperature exposure is the inherent variability in the properties of wood both in terms of the original strength properties and the properties being examined as indicator of strength loss. Rather than predicting specific values of MOE and MOR, results for many of these techniques are better for comparing damaged members to similar members that are outside the area of elevated temperature exposure.

NDE options

Visual and density determinations

The most obvious NDE determination of damage due to thermal degradation is visual. There can be various degrees of browning of the wood. Pyrolysed wood retains the original cellular structure as observed via light microscopy or scanning electron microscopy (Zickler et al. 2006). Zicherman and Williamson (1981) examined the microstructure of fire-damaged wood and found the demarcation between damaged and undamaged wood to be extremely narrow (several cell layers in thickness). Schroeder (1999) concurs with this observation of a narrow pyrolysis zone and attributed observations of a wider band to chemically-borne moisture migration. For woods with resin contents, extrusion of the resin is evidence of exposure to elevated temperatures.

As discussed, one detrimental outcome of the thermal degradation is the reduction in the density for wood exposed in temperature range of 200 to 350°C. Taking into account both mass and volumetric changes, the change in density equates to 60% of original density at temperature of 340°C (Zickler et al. 2006). From 600 to 900°C, the char density increases to about 80% of original density. Later at 1800°C, the density drops back to 70% of original density (Zickler et al. 2006). Thus, one option for NDE evaluation is to measure the density itself. A core sample can be removed to examine the density gradient.

Screw withdrawal

An extensive investigation of screw withdrawal as a NDE tool was for the evaluation of FRT wood damaged due to prolonged exposure to elevated temperature in roof applications has been conducted (NAHB National Research Center 1990, Winandy et al. 1998, Ross et al. 1991). The screw-withdrawal test relates the maximum extraction load to residual flexural properties. In an initial FPL study of thermally degraded FRT plywood, the regression of screw withdrawal resistance and bending strength had a correlation coefficient of 0.88 (Ross et al. 1991). In a more extensive study on FRT thermally degraded plywood (Winandy et al. 1998), the data from different treatment/thickness could not be grouped into a single universal model to predict the bending strength but models were developed for specific sub-groups.

The results obtained through screw-withdrawal tests were thought to be of value when comparing to similar members in the fire-damaged structure that have obvious degrees of degradation or residual load capacity. Kukay et al. (2008, Kukay and Todd 2009) developed equations including variables for moisture content, specific gravity, moment of inertia, maximum screw withdrawal load, cross-sectional orientation with respect to the pith, treatment group (charred or un-charred), and various interactions between these variables. They concluded that the results obtained through screw-withdrawal tests are best represented when the results are limited to comparisons to similar members that have obvious degrees of residual load capacity. Variability of the results stem from changes in: the predrilled pilot-hole size, the screw insertion depth, the screwtip to screw shank diameter, and the rate of extraction. For these reasons, care was needed when interpreting and extrapolating the results from screw-withdrawal tests. General correlations are likely to lack adequate precision to establish actual property values.

Micro indentations, penetration, hardness

In contrast to the screw withdrawal techniques that depend on a depth of thermal degradation, techniques based on hardness provide an indicator of thermal degradation near the surface of the wood member. The micro-indentation technique is much like that of a traditional hardness test. A 1.5 mm (lengthwise), 0.5 mm diameter pin is pressed into the wood member with a very precise loading. Hardness is the force required to indent a material a specified amount. There are various methods in wood hardness testing including the Janka method and the one specified by Branco et al. (2009). The amount of the pin that penetrates the wood has been used to generalize the mechanical properties of individual members. The penetration test, a variation of the micro indentation test, utilizes a larger pin. This test measures the amount of strikes of a rebound hammer that is required to drive the large pin into the member a certain distance. The Pilodyn test uses the depth of penetration of a spring-loaded pin as a measure of degree of degradation (Ross and Pellerin 1994).

Zickler et al. (2006) conducted nanoindentation tests on spruce wood that had been pyrolysed to temperatures up to 2400°C. The reduced elastic modulus remained fairly constant to temperature of about 280°C but then rapidly dropped to a broad minimum at 400°C. Starting at 500°C, the reduced elastic modulus increased to values (40 GPa) at 900°C, much higher than the room temperature values (~12 GPa), until decreasing again starting at about 2300°C. Likewise, hardness increases from 0.4 GPa at 220°C to approximately 4.5 GPa at 700°C and a reduction in values occurs starting at 2000°C. The indentation ductility index remained constant at about 0.8 until 300°C where it dropped to ~ 0.1 at around 500°C. Zickler et al. (2006) concluded that below 400°C, decomposition leads to a minimum of the elastic modulus. Above 400°C, there is a gradual transition from a visco-plastic biomaterial into a brittle, glass-like carbonaceous residue with maximum values at around 800°C. Above 2000°C, plastic deformability improves.

Resistance micro-drilling technology

An innovative technique that provides relative density gradients through the width of the member is resistance micro-drilling. Modern drill-resistance equipment usually consists of a power drill, a specialized drill bit, and a software/hardware interface to facilitate data collection and data analysis. Drill resistance tests are performed in much the same fashion as drilling a pilot hole, or a series of pilot holes into wood members. The results from a drill resistance test, however, are plotted as a function of penetration-depth zones that exhibit less resistance and can be noted for areas of possible decay. Drill-resistance tests have been traditionally classified as a quasi-nondestructive (semi-destructive) test as minor localized damage (~3 mm holes) is imposed on the member of interest during testing. Drill-resistance tests are a function of drill-bit insertion depth. Generally speaking, a decrease in drill resistance or rather, an increase in the drill-penetration rate can be correlated to areas of decay, and aid in the determination of the thickness of the residual shell (Emerson, et al. 1998).

Until recently there had been little research to apply micro-drilling to the evaluation of fire damaged wood. As part of a study on evaluating fire damaged components of historic covered bridges, four 127 mm x 305 mm glulam beams were subjected to a low temperature fire exposure in a fire test furnace. In a quick assessment of the application of technology to fire damaged wood, resistance micro-drilling measurements were made on charred beam near the mid-length of the beams in a vertical orientation. The fire-charred outer portion of the glulam beam has considerably less density than sound wood and was easily detected with this NDE tool. The resulting relative density profiles were utilized to estimate (1) the remaining depth of uncharred wood and (2) the thickness of the thermal damaged wood layer. It was much more difficult to estimate the thickness of the thermal damaged wood layer.

Sound/ Stress wave

Stress-wave evaluation is based on sound-wave physics. Stress waves (also referred to as sound waves) are generated from an impact on the surface of a member that is under investigation. Impact sound waves are measured as a function of their time to travel from one side of the member to the other side. The dynamic modulus of elasticity or apparent MOE (Pa) is considered equal to the wave speed (m/s) raised to the second power times gross density (kg/m^3) (Ross & Pellerin 1994). As with some other NDE methods, stress wave is a better predictor of MOE than it is for MOR. In tests of logs, Wang et al. (2004) found that both static and dynamic MOE decreased continuously as the log diameter decreased, apparently due to difference in the tree growth rate. The moisture content of the member must be known before the analysis can be completed. Since this test relies on stress waves quickly propagating through the member, it is essential that the exact distance between the first and second probes is known. Boundary conditions and their effects on wave behavior need to be considered (Ross et al. 1991). Stress-wave evaluation tests have long been used to detect decay in wooden members. They have more recently been used as indicators of residual wood stiffness for individual members.

Garcia et al. (2012) used stress wave for nondestructive determination of the MOE of wood before and after heat treatment. The dynamic modulus of elasticity decreased by about 13% in the most severe treatment (230°C for 4 h) but not for the milder treatments.

A strong relationship was found between energy absorption as measured by stress wave techniques and residual strength of degraded FRT wood but the speed of sound was insensitive to the degradation (Ross, et al. 1991). As part of a study on evaluating fire damaged components of historic covered bridges, four 127 mm x 305 mm beams were subjected to a fire exposure in a fire test furnace that resulted in a narrow char layer but a deep layer of elevated temperatures that penetrated beyond the base of the char layer by nearly 25 mm. As a result of the fire exposure, average measured values indicate: a 54% reduction in the maximum recorded load, a 46% reduction in strength (MOR) based on the residual cross-sectional area and a corresponding 20% reduction in stiffness (MOE). The results are based on a standard three point bending test with an increasing load applied at the lengthwise center of each beam. Sound wave measurements were taken near the top and bottom of each beam. The values and corresponding results were repeatable; resulting comparisons of the transmission rates indicated a reduction due to fire exposure. But the reductions in the times for fire exposure were not greater than the differences between the fastest and slowest times for the different specimens prior to fire exposure.

Ultrasonic

Ultrasonic inspection techniques consist of high-frequency stress waves that disperse quickly over a short distance in wood. Ultrasonic inspection has been used in manufacturing to estimate product quality and can also be used to detect common strength-reducing defects such as knots, slope of grain, and decay. MOE is computed from the sound wave measurements. Measurements for MOE are only valid for longitudinal measurements but the velocity and frequency domain signal amplitude are useful for defect detection in the transverse direction (Klinkhachorn et al. 1999).

Klinkhachorn et al. (1999) developed a portable ultrasonic device and conducted a few preliminary tests on charred yellow poplar specimens. There were little changes in the time delay or the velocity due to the charring of the two or four surfaces of the specimens but the area under Power Spectral Density (PSD) plots changed significantly as the result of the charring. Reinprecht and Panek (2012) have shown that ultrasound technology can be used to detect differential density in wooden members. In their study, sawdust was used to model rot in wood. The ultrasound waves that propagated through the media were significantly slower in comparison to a solid member.

Chemical analysis

Chemical analysis represents a different approach to NDE analysis of thermally degraded wood in that the effects being measured are the changes in the chemical composition of the wood. For initial exposures to heat, the extractives and the hemicelluloses are likely to be the first to be affected. Wood extractives such as fatty acids, fats, and waxes migrate to the surface of heat treated wood (Nuopponen, et al. 2003). Nuopponen et al. (2003) used FTIR spectroscopy to examined Scots pine that had been heat treated under steam at temperatures of 100 to 240°C. At temperatures of 100 to 180°C, the resin acids in the radial resin canals moved to the surface of the heat-treated wood and disappeared from the wood surface at higher temperatures (Nuopponen et al. 2003). While not providing a measure of strength loss, consideration of extractive content can provide indication of the level of temperature exposure.

In the thermal degradation process, the hemicelluloses are among the first of the three main wood components to be affected (LeVan and Winandy 1990). Potential parameters include holocellulose and alpha cellulose content and degree of polymerization (Ross et al. 1991). Hemicellulose measurements have potential to provide direct measure of strength loss since the xylose, galactose, and arabinose content were sensitive to the loss of mechanical properties (Winandy 2001). Arabinose was the most sensitive indicator of early strength loss. In a study on cyclic long-term temperature exposure at 82°C, 30% RH, only arabinose showed a consistent reduction with increased durations of heating (Green and Evans

2008). The cellulose is the last component to be affected by the elevated temperatures. Various investigators have used x-ray techniques to examine the crystallinity of the cellulose.

Reductions in the pH (increased acidity) of the wood are a potential indicator of thermal degradation and strength loss. Lebow and Winandy (1999) investigated pH of wood as technique for evaluating thermally degraded FRT plywood. Although some correlation ($R^2 = 0.74$) was observed between pH and strength loss in FRT plywood, this method was less sensitive to degradation in untreated plywood. In the investigation of options for assessing thermally degraded FRT plywood, expense and the specialized testing are often cited as disadvantages of the chemical analysis approach (NAHB National Research Center 1990, American Plywood Association 1989).

Near infrared

NIR technology works by analyzing the interactions between materials and electromagnetic radiation. The wavelength and line speed are both variables that are noted when creating prediction models for applications that historically have related to the detection of decay and other wood processing issues. Spectral analysis tests use infrared radiation to identify end products of chemical processes including thermal degradation. The NIR technology can be used to accurately measure the chemical composition, mechanical properties, and a select few anatomical properties of wood (Brashaw et al. 2009). Bachle et al. (2010) and Esteves and Pereira (2008) have investigated NIR spectroscopy to evaluate the properties of heat-treated wood. Other researchers have used this technique to predict surface moisture distribution as well as wet pockets. The ability to detect local variants as well as general material distributive properties like moisture content make this technique appealing to applications beyond quality control.

Mechanical Testing

Mechanical testing is a more direct approach to evaluating the effect of elevated temperatures on mechanical properties. In terms of NDE, this normally involves some sort of proof loading to determine the MOE. A bending proof load test was one of the options developed for the assessment of FRT plywood roof sheathing (NAHB Research Center 1990, Ross et al. 1991). As part of the study on fire-damaged components of historic covered bridges, a proof loading method specific to field application to fire-damaged wood components was developed (Kukay et al. 2013). Mechanical testing options include destructive methods such as removal of selected members for testing or removal of small samples for laboratory mechanical testing. Destructive testing will provide a direct measurement of modulus of rupture while proofing loading techniques only provide direct measurements of modulus of elasticity.

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Abstract

The 18th International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the USDA Forest Service's Forest Products Laboratory (FPL) in Madison, Wisconsin, on September 24–27, 2013. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 18th Symposium is captured in this proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

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