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INDUSTRIAL APPLICATIONS AND OPPORTUNITIES FOR NONDESTRUCTIVE EVALUATION OF STRUCTURAL WOOD MEMBERS

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ABSTRACT

This paper reviews techniques that can or have been used for determining the key properties of structural wood members, largely softwood lumber and structural panels. For solid wood materials, moisture content, density, and defects are underlying basic properties that must be assessed independently to arrive at structural values. In reconstituted materials, an additional variable, adhesive quality dominates. In addition to reviewing these properties, an assessment is provided for the state of maturity of the relevant technologies.

Keywords: microwave, density, moisture content, mechanical properties, grading, radiation, adhesive bonding, adhesive curing, grain orientation, internal defect scanning

INTRODUCCTION

Nondestructive evaluation (NDE) applies to the processing stage and properties of interest within that stage. For example, processing stages would include evaluation of logs in a sawmill before breakdown to lumber and the subsequent steps to create products. The major materials properties groups would include basic properties, mechanical properties, defects, and bonding quality. Basic properties include moisture content, density, and grain orientation. Moisture content and density measurement technologies could be considered mature, with many available commercial devices. Defects can include natural (from wood growth) or from exposure in growth or manufacturing. Some of these are confounding, such as decay or grain separations that can occur in virtually any stage. Bonding quality relates to both the adhesive curing process and quality of adhesion. The purpose of this paper is to review NDE techniques that are applicable to structural wood members, such as softwood lumber and structural panels, and briefly discuss the limitations and opportunities for commercial applications. More detailed background of these techniques can be found in recent proceedings and books (Pellerin and Ross 2002, Beall 2002, Bucur 2003, Bröker 2005).

BASIC PROPERTIES SENSING

Moisture content.

By far, the widest used technology for non-intrusive moisture content sensing has been electromagnetic. The typical RF meter electrodes always have a component of the electric field along all three major axes of wood, therefore, the influence of grain angle on electrical properties must be considered. Two types of RF moisture meters are commercially available (James 1963). Power loss meters react primarily to resistance and capacitance (or admittance) meters are more sensitive to dielectric constant. Both types of meters have arbitrary readout scales because of the effects of density and species. A dual-frequency moisture gauge (10 kHz, 312.5 Hz) was developed to measure lumber moisture

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content on line, with the two frequencies used to compensate for distance to the single-sided sensing heads (Parker and Beall 1986).

Density sensing.

Radiation (gamma or X-ray) has been used for density measurements in internal defect scanning of logs, weigh scales for composite product panels, and density determination of lumber in mechanical grading. In measurements of the combination of wood and moisture, the mass attenuation coefficients of each must be considered (Olson and Arganbright 1981, Laufenberg 1986, Winistorfer et al 1986, Karsulovic et al 1999). Density of wood-based composites can also be measured using microwave technology by obtaining attenuation and phase change to measure moisture content and density (King and Basuel 1992).

Grain orientation sensing.

An optical technique has been used to determine the diving grain angle in lumber, taking advantage of the characteristics of reflected light from the surface (Matthews and Soest 1984). The response of the wood has been called the "tracheid effect," since it was used on the vertical cells in softwoods (tracheids). One electromagnetic approach is based on the variation of dielectric properties with grain orientation, using rotating sensing heads (McLauchlan and Kusec 1978).

Combined sensing techniques.

There are a number of applications that use more than one technology to sense basic properties. One example is the use of radiation density gauges with microwave systems to provide independent input of total density. For materials such as composite panels, which have relatively low moisture contents, the absorption of radiation is largely by the wood material, therefore it is a good measure of density (King and Basuel 1992). There are also opportunities with microwave systems to measure density, moisture content, and grain orientation simultaneously and independently, which can be done by measuring phase, amplitude, and depolarization, respectively (King et al 1985).

MECHANICAL PROPERTY SENSING

Mechanical properties are influenced by basic properties (moisture content, density, grain orientation) as well as defects. Machine grading is a term is used for a number of techniques used to arrive at design properties for solid-sawn lumber, including stiffness- and density-based grading (Boström 1994, Müller 1968, Ziegler 1997). Measurement of mechanical properties of structural composite panel products is an emerging technology that operates analogously to the machine grading process.

Stress wave propagation.

This method uses mechanical longitudinal excitation to determine apparent elastic modulus by $E_{a.} = kc^2\rho$, where E_a is the apparent MOE, k constant, c the propagation velocity, and ρ the density. The value for density may require empirical determination. Stress-wave methods have been applied to solid wood, reconstituted wood-based materials, mechanical property evaluations in veneer grading for use in laminated veneer lumber, and defect detection of decay and delamination (Ross and Pellerin 1991, Sandoz 1992, Sandoz 1996, Green 1997).

Microwave technology.

Microwave transmission is a sensitive means of obtaining average local grain orientation and has been used in commercial machines such as the Finnograder, where a nuclear gauge compensates for density and moisture content effects on attenuation. Another approach has been to use microwave with a vision system to aid in detection of sound knots, which do not have sufficient visual contrast with clear wood (Choffel and Martin 1996).

Radiation technology.

X-ray scanning to predict strength from local density has been introduced as an alternative to machine grading (Schajer 2001, Ziegler 1997), taking advantage of the fact that density of knots is greater than that of the surrounding clear wood. A resolution of about 2% was achieved using three detectors over the width of the board.

INTERNAL DEFECT SENSING

Considerable work has been conducted in an attempt to develop a reliable means of detecting decay in structural wood components (Szymani and McDonald 1981, Ross and Pellerin 1991, Beall and Wilcox 1987, Wilcox 1988, Patton-Mallory and DeGroot 1990, Madsen 1994). These methods include radiographic, electrical, mechanical, and acoustical techniques.

Detection of defects in logs.

There have been a number of studies on detection/imaging of defects in logs (Birkeland and Holoyen 1987, Burgess 1985, Chang 1989, Chang and Guddanti 1993, Chang et al 1991, Chang et al 1987, Faust et al 1996, Hailey and Swanson 1987, Han and Birkeland 1992, Javaadpour et al 1996, Månson 1991, Roder et al 1989, Wagner et al 1989). Recent improvements in data processing have made the CT technique at least conceptually possible. Several other sensing technologies have been considered—Magnetic Resonant Imaging (MRI) and microwave. Microwave tomography has been proposed as a candidate and could substantially lessen the scan time, although it is unclear if the resolution is adequate. The initial log scanning with radiation dates back to the late 1960s, with the development of the TINA log scanner (Månson 1991), which evolved into a means of sorting logs by the perceived grade variations from the images. In an approach to reduce the data from images from X-ray CT scanning, Grundberg and Gronlund (1991) increased the pixel size from 0.5 to 5 mm, reduced the gray scales to five levels, and introduced techniques to overcome limitations in the images. One approach to integrating on-line sawing decisions with CT scan information was the superposition of a virtual sawblade on the cross-section to permit adjustments in cuts based on the sawyer observation of defects and grain orientation (Chang and Guddanti 1993). In the typical operation of MRI, a number of responses from linear projections are combined to obtain a single slice of the cross-section. MRI has two distinct advantages over other radiation techniques: the lack of ionizing radiation and the ability to uniquely classify a chemical state of each voxel. MRI has evolved to much smaller magnetic fields and open systems, creating much more flexibility and reducing the complexity and cost of the system. Ultra-fast MRI scanners are now available that can produce 10 images/s, although with much less resolution (Chang et al 1991).

ADHESIVE BONDING SENSING.

Virtually all studies on bond quality and many recent ones on adhesive curing are based on ultrasonic technologies (Beall 1990, 1991).

Bond quality in laminates.

In one of the first studies on wood laminate bond quality (Reis et al 1990), single-paired laminates were made with various adhesive bond defects, tested in through-transmission. The ultrasonic parameters (RMS area and peak amplitude) showed high correlations with shear failure before and after conditioning. A subsequent study on finger-jointed material gave similar correlations (Reis et al 1990a). This ultrasonic technique was also used by Anthony and Phillips (1992) in developing a process control system to evaluate the quality of fingerjoints in tension members of wood. Methods for statically and dynamically measuring laminate bonding quality have been developed (Beall and Biernacki 1994, Biernacki and Beall 1993).

Panel evaluation.

The first such reported use of ultrasonics for panel evaluation was to determine the effect of additives on the quality of hardboard (Reis and McFarland 1986). Studies run on specially-prepared particleboard having low and high density, and low and high resin content, provided a range of internal bond strengths that correlated well with ultrasonic outputs (Green 1988). Subsequently, a number of studies were done on larger and increased numbers of panels, which led to a patent (Shearer et al 1988) for an on-line system.

Adhesive curing in laminates.

There have been a number of studies to evaluate the curing process of adhesives. Several adhesives were studied using wood adherends with an RMS output to quantify the development of modulus, and therefore the curing of the bonds (Beall 1987, 1989). This work was continued using full-size laminating material (Beall and Biernacki 1992; Biernacki and Beall 1996, 1996a).

Adhesive curing in panels.

There are experimental dielectric methods to measure changes in the electric field from either an inserted probe or the use of a portion or all of the platens as electrodes. Infrared spectroscopy uses an optical fiber to measure radiation associated with heat generated, with the obvious limitation of sensitivity only to exothermic reactions. These methods of curing monitoring can assess the solidification of the adhesive, but not all of the phases of bond curing, interaction with the adherend, or the final quality of bond. In an ultrasonic approach that relates to all of these phases (Beall and Chen 2000), tone-burst energy was transmitted through press platens to assess the development of the bond in situ.

LIMITATIONS AND OPPORTUNITIES

NDE sensing of the properties of wood and wood-based materials must cope with growth characteristics and defects that arise from the complex growth processes of this biological material. Also, defects occur in the manufacturing process that can be obscured by existing defects and basic properties. As a final challenge, degradation that occurs in the material in service can be very difficult to detect. There are some observations that can be made in the context of these special needs:

1. Technologies exist for detection of basic properties, especially for moisture content and density, however, determination of grain orientation, which is that major determining parameter affecting strength, requires more complex technologies that have not been widely introduced.

2. Techniques are being developed to measure mechanical properties that will ultimately supercede the current machine grading, which has substantial limitations. These techniques are non-contacting and are based on detection of grain angle or density to infer strength. It is unlikely that a single technology will be sufficient to fully displace machine grading.

3. Detection of internal defects of logs is a technology-driven effort, with severe technical and economic limitations. One of the major problems is that there are several developing technologies, most of which are better suited to medical use than in harsh operating conditions. Until artificial intelligence or other inferential methods are more completely developed, it is very unlikely that such an overwhelming volume of data can be adequately processed and utilized.

4. Adhesive bond curing and bond quality can be detected quite effectively with ultrasonic techniques. The development of these techniques has aided the use of ultrasonics for other applications, such as decay detection.

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