Within-board lumber density variations from digital X-ray images

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Abstract

Computed radiography (CR) is a potentially practical method to obtain density and internal structure characteristics of lumber for a variety of processing and grading decisions. A CR method is presented to obtain within-board density variations and knot sizes in southern pine lumber. The method will be used in conjunction with grain angle scanning to more fully characterize the unique mesostructure of individual boards. These characterizations will be used in a computer model to simulate the mechanical response of boards. A calibration method has been developed to transform exposure readings to density readings on a 0.9- by 0.9-mm grid. Preliminary comparisons of CR density with gravimetrically determined density for 35- by 35- by 35-mm small clear blocks indicates an average difference of approximately 1 percent. Further refinement and verification of the method is continuing. Examples of density variation in the vicinity of knots are presented and discussed.

Introduction and purpose

Computed radiography (CR) offers a means to rapidly assess localized changes in density within individual pieces of lumber. Previous research has shown that specific gravity within a board increases dramatically in and around a knot, and has shown that these increases correspond to localized increases in tensile strength perpendicular to grain (1). The overall research objectives are to nondestructively measure mesostructure characteristics of boards, such as density variations, and to establish the link between mesostructure and structural performance. Mesostructure is the middle level of detail between characterizing cell structure at the microscopic level and traditional treatments of wood as a homogeneous solid. Previous mesostructure characterization has focused on identifying grain angle variations and their relationship to board fracture patterns (3,4). In this paper, we present an additional level of detail by identifying within-board density variations with CR. This equipment used is unique, but likely not prohibitively expensive for applications in the wood products industry. The long-range goal of this research is to provide fundamental methods and information for making edging, trimming, and grading decisions in the production of lumber.

Relevant literature

Radiation densitometry is a commonly used technique in dendrochronology (2,5,21,22) and in determining density profiles of some wood composites (17,23). The use of this technique in obtaining density distributions within lumber...
specimens to aid strength prediction is new. The method provides a detailed picture of density changes within a specimen. The use of X-ray radiation for density analysis was developed in France (22). Other forms of electromagnetic radiation such as gamma rays and beta rays have also been employed in density analysis (6,13-15,24). Different investigators have used different methods of scanning regarding the relative position between object and X-ray source, namely fixed object/moving X-ray tube, moving object/fixed X-ray tube, and fixed object/fixed X-ray tube (2,7,8,11-14,20). This paper describes a digital X-ray scanning method using a fixed object and fixed X-ray tube.

The principle of scanning densitometry is to pass a collimated photon beam through a specimen and into either a radiation sensing device (photocountillation detection system) or a combination of X-ray film and intensifying screens. Most radiation densitometry utilizes the former because of difficulties associated with film processing and density determination from film. The method described in this paper, however, uses neither a scintillation detector nor X-ray film, but rather a photostimulable phosphor plate.

By recalling how X-rays are produced and how they interact with an exposed object, one can explain why there is always some deviation in density determination using X-ray scanning techniques. X-rays are produced in an X-ray tube when electrons accelerated from the cathode strike the anode due to a given potential difference. When an electron is stopped by nuclei in the anode, a large amount of the electron energy is converted to heat and the rest appears as X-rays. All electrons striking the anode have the same energy, but the X-rays produced have many different energies. As a result, the X-ray intensity received by an exposed object is not uniform from point to point.

X-rays interact with an exposed object in three ways, namely coherent scattering, photoelectric interactions, and Compton scattering. The total interactions govern the mass attenuation factor defined as the fractional reduction of X-ray intensity per material density per unit thickness. Coherent scattering, the change in X-ray photon direction without energy transfer, is most clearly identified with lower energy X-rays. Coherent scattering has little effect on wood densitometry except for a slight blurring of edges. In photoelectric absorption, on the other hand, the X-ray photon is completely absorbed by the exposed atom. Energy transfer, the amount of which depends on the atomic number of the exposed atom, happens in this interaction. In wood material, the main elements are C, O, H, and N with atomic numbers 12, 16, 1, and 14, respectively. Photoelectric absorption is responsible for the major difference in radiographic appearance (contrast) between higher and lower density regions in an exposed board. In the third kind of interaction, Compton scattering, the X-ray photon transfers some energy to the electrons of the exposed material, and proceeds in a different direction with a reduced energy. Because Compton scattering is almost completely independent of atomic number, it is approximately the same for all materials and depends only on the incident X-ray energy (9). The total effect of these three X-ray and material interactions appears in the following equation:

\[ \mu_m = \mu_{\text{coherent}} + \mu_{\text{photoelectric}} + \mu_{\text{Compton}} \]  \[1\]

where:

- \(\mu_m\) = mass attenuation factor

Clearly, depending on the compositions of the main elements, the mass attenuation factors are not uniform among species (10). Within a lumber specimen, however, the mass attenuation factor can be assumed constant, in accordance with the homogeneous material assumption.

A specially designed filter grid can be used to reduce scatter. It consists of thin flat sheets made of alternating lead and aluminum. Lead strips are designed to attenuate the scattered radiation and the aluminum interspace to allow the passage of the primary X-ray radiation. Another simple way is by using an air-gap scatter reduction scheme where some distance is maintained between the specimen and the X-ray film.

The intensity of the collimated beam of monochromatic X-ray radiation after it has passed through some absorber of thickness \(t\) may be determined using the following attenuation equation (15):

\[ I = I_o e^{-\mu t} \]  \[2\]

where:

- \(I\) = intensity of the radiation beam after passing through the wood (counts/unit time)
- \(I_o\) = intensity of the radiation beam before passing through the wood (counts/unit time)
\[ t = \text{thickness of absorber or exposed material (unit length)} \]
\[ \mu = \text{linear attenuation factor (unit length}^{-1}) \]

The linear attenuation factor represents the fractional number of photons absorbed from a beam of radiation per unit length of path of the absorber. As mentioned earlier, the magnitude of attenuation is dependent upon the source of radiation and the atomic numbers of the elements of the absorber. Therefore, transmitted radiation can be defined as:

\[ I = I_0 e^{-\mu_m \rho t} \]

where:
\[ \mu_m = \text{mass attenuation factor of the absorber (cm}^2/\text{g}) = \frac{\mu}{\rho} \]
\[ \rho = \text{density of the absorber (g/cm}^3) \]

Mass attenuation factor is a material property. In general, it depends on the constituent elements in the material and the energy of radiation. Clearly, in wood, it also depends on the moisture content because water has different constituent elements than solid wood. Olson and Arganbright have estimated the mass attenuation factors of several wood species at different energies using elemental mass attenuation factors weighted by their respective wood elemental compositions \(18\). These contributions are based on photoelectric interactions only and neglect possible contributions from coherent and Compton scattering. Computed mass attenuation factors varied among investigated species (pine and larch) at each X-ray energy below 40 keV. However, above this energy the factors were essentially the same at each energy, regardless of difference in constituent elements in wood.

Equation [3] can be written in the form of

Equation [4] can be used to find the density, \(\rho\), when \(I\) and \(I_0\) or the proportion of \(I/I_0\) is known. These two radiation intensities can be obtained using an X-ray scintillation detection system, for a constant \(t\) and small aperture area. This area should be so small that no density variation occurs over the area \(16\).

Computed radiography is a “filmless” radiography. X-ray images are captured and converted to digital signals, which can be stored or retrieved using disk storage. CR allows customization of contrast and resolution of an X-ray image. Quality images can be obtained even with low radiation levels. Another advantage of CR is that the image plate is reusable. Figure 1 shows the image plate process from exposure to erasure \(21\).

As seen in Figure 1, CR uses a scanning laser stimulated luminescence produced in an image receptor plate exposed to X-ray radiation, and converts the light to digital data. The image plate, coated with photostimulable phosphor crystals, replaces the conventional film/intensifying screens as a medium to detect and record a high-quality image. The phosphor crystals act as energy traps when exposed to ionizing radiation.\(^1\)

In both conventional X-ray radiography and CR, several factors can affect the quality of X-ray radiographs, such as fluctuation in supply voltage to the X-ray generator, lack of uniformity in sample thickness, and moisture content of the wood \(19\). The effect of fluctuation in supply voltage to the X-ray generator can be addressed by using a very short exposure duration. Sample thickness and moisture content can be controlled by careful sample preparation.

**Method, resolution, and accuracy**

In the present study, X-ray scanning is used to gather within-board density information. The

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\(^1\) X-rays and γ-rays are examples of ionizing radiation. They have enough energy to separate one or more electrons from the atom to produce an ion pair.
Department of Radiology and Medical Physics at the University of Wisconsin, Madison, Wis. provided access and technical assistance in using the X-ray tube and digital scanning equipment.

To obtain high-quality radiographs of a wood specimen, the X-ray source was positioned 18.10 mm from the image plate to reduce parallax distortion (19). Each plate was exposed for 0.5 seconds and the electrical current was 200 mA. Both the air gap technique (152 mm) and a filter grid with a 3.2- by 3.2-mm grid layout were used to reduce X-ray scattering. The energy level of the X-ray source was 50 keV. These parameters were kept constant throughout the study.

The image plate was digitally scanned after X-ray exposure using the Philips Computed Radiography (PCR) System to produce readings on a 0.18- by 0.18-mm grid over a 319- by 388-mm (14- by 17-in.) area resulting in almost 19 megabytes of ASCII data. For simplicity, data was reduced to a 0.9- by 0.9-mm grid. The readings were machine-dependent numbers ranging from 1 to 1024 and were influenced by parallax and scatter. A reading of 1 indicated highest radiation exposure and a reading of 1024 indicated lowest radiation exposure. We denote the digital representations as PCR values.

According to the specification of the PCR system, the correlation between the PCR value and the X-ray radiation is:

$$E = \frac{200}{S} \times 10^{(512 - PCR)}$$  \[5\]

where:
- \(E\) = radiation exposure in milliRoentgen (mR)
- \(PCR\) = PCR value
- \(L\) = laser reader parameters
- \(S\) = laser reader parameters

The value of \(L\) controls the reading range of the PCR values. It can be preset via the control panel of the system. A value of \(L=1\), which lets the laser reader read the entire range of the image, was chosen. The value of \(S\) controls the reading sensitivity. It cannot be entered directly by the user and is calculated by the PCR system.

As mentioned earlier, density can be obtained by using the standard attenuation equation, i.e., Equation [4]. The ratio of \(I/I_0\) in Equation [4] is equal to the ratio of \(E/E_0\) where \(E_0\) is defined as the X-ray radiation in mR without any absorber. Therefore, the radiation exposure at any point, if there is no absorber, can be expressed as:

$$E_0 = \frac{200}{S_0} \times 10^{(512 - PCR_0)}$$  \[6\]

where:
- \(PCR_0\) = PCR value, if there is no absorber
- \(E_0\) = radiation exposure in milliRoentgen (mR)
- \(S_0\) = laser reader parameters

To evaluate these constants, we employed two small specimens called calibration samples. Gravimetric densities of both specimens were substituted into Equation [8] to yield Equation [9] containing unknowns A and B. Constants A and B are the solution of the resulting linear simultaneous equations. A unique solution will result from two distinct values of thicknesses, \(t_1\) and \(t_2\), of the calibration samples 1 and 2, respectively in the path of the X-ray.
As discussed earlier, mass attenuation factor $\mu_{aq}$ is a material property that depends on the X-ray energy. In the case of wood, it depends not only on solid wood content, but also on moisture content. To investigate the effect of moisture content on mass attenuation factor, we conducted X-ray exposures of southern pine under moisture content conditions of 12 percent and ovendry. Twenty small wood blocks at 12 percent moisture content were exposed to X-rays. The gravimetric density of each block was measured and substituted into the theoretical equation (Eq. [7]) to obtain its mass attenuation factor. The average mass attenuation factor was 0.2506 cm²/g with a coefficient of variation of 1.1 percent. Similarly, ten small blocks were ovendried for 39 hours at 103°C and exposed to X-rays. The mass attenuation factor for dry wood was only 1 percent lower than wood at 12 percent moisture content. As a result, we adopted a constant mass attenuation factor of 0.2506 cm²/g for the entire range of moisture contents studied. That compares to a value of 0.206 computed by Olson and Arganbright considering the photoelectric effect only (18).

Densities of full-width lumber specimens (38 by 140 mm and 30 by 89 mm, length 160 to 400 mm) and small blocks (35 by 35 by 35 mm) were gathered using the complete procedure outlined in Figure 2. CR densities were compared to gravimetric densities. Gravimetric densities relied on caliper measurements to the nearest 0.1 mm and weights to the nearest 0.001 g. Even exercising the utmost care, some small errors are inherent in the gravimetric technique. It was found that the maximum difference from the two measurement techniques for small clear blocks was 6.1 percent and that for actual size lumber specimens was 3 percent. Figure 3 shows a comparison between gravimetrically measured densities and CR densities. Using the method described earlier, data were collected from several exposures on different days and different moisture content conditions (12% and ovendry) using 123 samples. The correlation coefficient ($r^2$) between the two types of readings was 0.97 and the average error was 1.3 percent.

Density patterns around knots

Using the above method, we conducted a small preliminary investigation of density patterns around

![Figure 2. Schematic of the CR density determination method.](image-url)
knots. Five specimens, consisting of 520-mm lengths of 38- by 140-mm (2- by 6-in.) southern pine each containing a single wide-face knot ranging in size from 30 to 45 mm in diameter, were subject to X-ray and data analysis. The results are summarized in Table 1. On average, the density within the knot increases by a factor of two above the average specimen density. High-density zones were defined as regions that possessed a density 20 percent higher than the specimen average. These high-density zones, in all cases, included the whole knot-wood region and also a transition zone of deviated grain in the clear wood. As indicated by Bethge et al. (1), this increase in density in the transition zone is tied to increases in perpendicular-to-grain tensile strength. This suggests that the natural growth process attempts to compensate for the high grain angles and weakening effect of a knot by increasing density in the high-density transition zone. Table 1 reveals that the width of the high density zone varies considerably from 1.0 to 1.7 times the transverse knot diameter. The length of the high-density transition zone varies from 1.1 to 1.4 times the longitudinal knot diameter. It is postulated that the absence of this transition zone in edge-knot situations reduces the strength that would otherwise be achieved.

Figures 4 and 5 show the variation in density along transverse lines (Fig. 4) and a longitudinal line (Fig. 5) running near or through the knot in sample 5. The visual knot size and location is superimposed over the density lines in these figures. The transition zone clearly lies outside the visual boundaries of the knot, especially in the transverse direction. In all cases, this transition zone of increased density is within one knot diameter of the knot center point. It has been known for some time that visual knot sizing does not capture the grain deviation associated with a knot. Figures 4 and 5 combined with the data in Table 1 indicate that visual knot sizing does not fully identify the region of high density associated with a knot.

Summary and conclusions

The primary objective of this study was to gather within-board density variations of lumber. This was achieved through the development of a unique but simple method utilizing digital X-ray scanning and the PCR system to provide density maps on a 0.9- by 0.9-mm grid. A calibration technique utilizing a nonsampled exposure and two small calibration specimens was developed to improve accuracy. Although many factors, such as nonuniformity of X-ray exposure and the prediction of mass attenuation, played important roles in the discrepancy of the radiographic densities, comparison with gravimetrically determined densities for small clear blocks indicates an average difference of only 1 percent. This method will ultimately be combined with grain angle data and utilized in new strength prediction models.
Application of the CR method has revealed knot densities that are twice the average board density in southern pine samples. Most importantly, a transition zone between knot and clear wood exists along the outer boundaries of a knot where density increases dramatically. Previous research suggests the increased density in the transition zone is tied to an increase in perpendicular-to-

**Figure 4.** Density variation along the transverse direction (width) of a 38- by 140-mm (2-by 6-in.) sample of southern pine containing knots.

**Figure 5.** Density variation along the longitudinal direction (length) of a 38- by 140-mm (2-by 6-in.) sample of southern pine containing knots.
grain tensile strength, suggesting that the transition zone attempts to compensate for the weakening influence of the knot.

**Literature cited**


