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NDE APPLIED TO THE CONSERVATION OF WOODEN PANEL PAINTINGS

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Abstract

Various nondestructive methods for determining the condition of wooden panel paintings have been investigated. Methods are being developed to detect voids, hidden cracks, and fine fractures that are often a source of premature failure in such objects. Computer analysis shows that cracks in wood promote severe stress concentrations which are aggravated by the mechanical constraints imposed on the wood by the construction of a panel painting.[1] The panel's structural condition needs to be mapped in a nondestructive fashion in order to predict how these objects will mechanically respond over time or in different environments. Decisions can then be made as to whether an object can be safely removed from storage, if it can withstand conservation treatment, if it can be continuously displayed, or if it can be safely shipped to special exhibitions. We have demonstrated the NDE capabilities of different techniques by examining standard panels of white oak (*Quercus* sp.), tulip poplar, hard maple (*Acer* sp.), true mahogany (*Swietenia* sp.), black cherry, and western fir (*Abies* sp.). The panels contain voids between 0.15 and 0.6 cm in diameter and cracks smaller than 0.02 cm. The techniques for investigation included x-ray radiography, xeroradiography, and ultrasonics. Results show that both x-ray radiography and xeroradiography techniques can easily find voids at least as small as 0.15 cm. Xeroradiography has benefits over x-ray radiography because its edge enhancement property enables flaws to be displayed prominently. At certain angles, cracks less than 0.02 cm were easily seen. The results of using these two techniques on a panel painting are discussed. Ultrasound techniques using an all-air coupled system and a hybrid air-coupled/dry-coupled system have shown promising preliminary results for finding voids and cracks.

Introduction

Wood has been a support for paintings through the ages. There are a variety of cuts, and species of wood possible depending upon the epoch, the country of origin, and the workshop in which the panel painting was made.[2] The possible layers that make up a panel painting include: the wooden support, the glue layer, the ground or gesso layer, the underdrawing, the imprimatur, the underpaintings, the paint layer, the glazing, the varnish, and any retouchings.[3] Cennini's 1437 treatise explains the craft in great detail.[4] The panels are usually cut either radially, which is more uniform in its dimensional response to relative humidity changes, or tangentially (Figure 1). Radially cut panels are usually between 0.7 and 1.5 cm thick, while tangentially cut panels are 4.0 to 6.0 cm thick.

Although many of the panels still exist today, there has been considerable concern with their deterioration for centuries.[5,6] Panels are dimensionally less stable with changes in relative humidity, especially when they have been thinned down and restrained during "conservation treatments". Studies are underway at various institutions including the Conservation Analytical Laboratory at the Smithsonian Institute, the Canadian Conservation Institute (CCI) in Ottawa, the National Gallery of Art in Washington, D.C., and the Tate Gallery in London, to examine the risk caused by incorrect travelling or storage conditions.

The structure of wood is well-known.[7] The anomalies that exist naturally and that may evolve need to be studied to understand results from different NDE techniques. Different natural inhomogeneities in wood include seasonal growth rings, knots, and ray cells, which are sheets of cells that grow in a radial direction along the longitudinal radial axis of the tree (Figure 1). Voids are often created by insects, including the common furniture beetle, (*Anobium punctatum* in the anobiidae family), the death-watch beetle (*Xestobium rufovillosum)*, the powder post beetle (Lyctidae), termites, and ants.[8,9] The tunnels can be as small as 1 mm and can lead to a completely riddled panel. The panel is then weakened, allowing cracks and breaks to occur more easily. Cracks also appear in panel paintings because of changes in the relative humidity that cause dimensional changes.[6,7,10,11] When restrained, wood compresses with water adsorption, crushing wood cells. Wood develops tensile stress and cracks with desorption. The structure of wood leads to severe anisotropic behaviour as the dimensional changes are greater in the radial and tangential directions than in the longitudinal direction. Both the adsorption and desorption of water can, therefore, lead to warping and splitting of the wood. The expansion and contraction of the wood can also cause the ground and paint layers to crack, cleave and buckle if they are not flexible.

Nondestructive Testing Techniques

The wood industry has used a variety of nondestructive techniques including: visual tests, ultrasonics, stress-wave measurements, vibration tests, x-ray radiography, computer aided tomography (CAT), collimated photon scattering, magnetic resonance imaging (MRI), acousto-ultrasonics (AU), acoustic emission (AE), microwaves, pulsed electric current, and even the skills of sniffer dogs to discover rot in buildings. Many industrial x-ray studies have been concerned with wood-boring insects. Ultrasonics has been compared to other methods to determine quality, strength, elastic constants, and degree of deterioration of wood. The theory, experiments, and viabilities have been discussed in many articles and proceedings.[12,13]

The museum conservation field has used many different nondestructive techniques on many materials. A few examples include: x-ray radiography,[14] which has been used extensively; xeroradiography,[15,16] on ceramics, porcelain, Egyptian faience, and underdrawings of paintings; ultrasound,[17-19] on murals, masonry, and wetted archaeological woods; infrared thermography,[20,21] to find deterioration in wooden panel paintings; x-ray computer tomography;[22] visible light; ultraviolet radiation; and other techniques. The first four techniques, x-ray radiation, xeroradiography, ultrasound with various coupling techniques, and infrared thermography were used in this study. Infrared thermography had only limited success and, therefore, will not be discussed further. In previous published studies, x-ray radiography and xeroradiography have not been compared while trying to map out the voids and cracks found in panel paintings; some work in this area has been performed at CCI. Air-coupled and dry-coupled ultrasonic systems have not been used on art objects, including wooden panel paintings.

Experimental Procedure

Samples

The samples used throughout the present experiments were six panels of wood, each with dimensions 40 cm x 23.5 cm x 3.5 cm. The six species of wood, with their densities were: white oak (*Quercus* sp.) (720 kg/m^3),[23] tulip poplar (460 kg/m^3),[23] hard maple (*Acer* sp.) (660 kg/m^3),[23] true mahogany (*Swietenia* sp.) (545 kg/m^3),[24] black cherry (530 kg/m^3),[23] and western fir (*Abies* sp.) (410 kg/m^3).[23] The panels were approximately at 12% moisture content.

In order to simulate voids and flaws in the panels, holes of different diameters (0.6, 0.4, 0.35, 0.2, and 0.15 cm) were drilled into the sides of the panel at different depths from the surface, as shown in Figure 2. The holes closest to the surface were between 0.2 and 0.5 cm from the surface, the next closest were 1.0 cm, and the furthest away were between 1.5 and 2.0 cm from the surface. On each side, a solitary 0.35 cm diameter hole was drilled 1 cm from the surface. The cracks in the sample panels occurred naturally from swings in relative humidity. These cracks of different sizes and lengths occurred in the white oak, hard maple, true mahogany, and western fir panels.

An oak panel painting, probably made around the turn of this century, (Figure 3a) was x-ray radiographed and xeroradiographed (Figures 3b and 3c). The width and length of the panel were 20 x 30 cm^2. The thickness was 0.7 mm at the edges, and it tapered to 1.2 cm in the centre. This panel had a number of cracks along the grain, at the top and bottom edges of the panel (less than 0.1 cm) and some voids (around 0.1 cm in diameter). As this painting is part of a research collection at the National Gallery of Art in Washington, D.C., strain gauges and metal wires had been attached to the back of the painting for another set of experiments. These are visible on the radiographs. The painting shows a winter scene of a house surrounded by trees with eight figures at the bottom. The pigment had been laid directly onto the wooden oak panel. A white pigment was used a great deal, for example in the areas surrounding the figures, the house, and the trees. This allowed the picture to be seen on the radiographs.

Techniques

Each panel was x-ray radiographed. The hard maple panel is shown as an example (Figure 4a). A Philips' MG 320 Constant Potential X-Ray Unit was used. This included a 300 kV double focus tube and a tube current of up to 10 mA. A small focal spot of 1.5 mm was used. The distance from the tube to the film was 125 cm. The film (Kodak M industrial large) and a 1 mm sheet of lead, which lay under the film, were placed in a vacuumed envelope. The settings used were 80 kV, 2 mA, for 3 minutes. Each wooden panel was xeroradiographed. A positive and negative image of the hard maple panel are shown (Figure 4b and 4c). A XEROX 125 System was used. The plate could only image half of each panel with some overlap, therefore two images needed to be taken for each panel. This caused the horizontal line seen in the xeroradiographic image. Both positive and negative images were taken. For the positive images, the settings were 42 kVp, 300 mA, for 0.4 seconds. For the negative images, the settings were 44 kVp, 300 mA, for 0.3 seconds. The panel painting was x-ray radiographed at the National Gallery of Art, in Washington, D.C., using the settings 25 kV, 50 mA, for 12 seconds. The xeroradiographs of the painting were taken using the same equipment as for the wooden panels and the settings 45 kVp, 10 mA, and 0.2 seconds. Both radiographs were taken from the front of the painting (Figures 3b and 3c).

The first ultrasonic set-up used an all-air coupled configuration (Figure 5). The transducers could be positioned anywhere over the tulip poplar panel. A unipolar, burst pulser (3 Ω impedance, 450 V) generated the signal which was then sent through an impedance-matching network (high-pass inverter). Both air transducers were 0.5 MHz, with 1-inch diameters face-plates and 2-inch focal lengths. They were both 0.8 inches away from the sample and were therefore defocussed on the sample. They were also off-set by 0.5 inches along the horizontal axis. One transducer sent the signal through the sample and the other received it after it traversed through the sample. The signal was then sent through a very low-noise bipolar amplifier, two precision attenuators (12 x 10 dB and 12 x 1 dB), a band-pass filter, and a linear detector. The transducer-transducer spacing was fixed by a "U-shaped" holder. The second set-up was a hybrid air-coupled/dry-coupled through-transmission configuration on the white oak panel. The set-up was identical to the previous one, however, the signal was transmitted through an air-coupled transducer (0.5 MHz, 1-inch diameter, 2-inch focal length, and 0.9 inches from the surface) and was received by a dry-coupled transducer (ULTRAN WD 50-1, 113065, 0.5 MHz, and 0.375-inch diameter). Scissor-like tongs were used to hold the transducers.

Experimental Results

The results showed that all voids were clearly seen with both radiographic techniques. The xeroradiographic technique displayed cracks in the maple panel at its bottom edge, which were smaller than 0.02 cm and which the x-ray radiographic technique did not show as well. Other features include mineralization pockets (in the central region), which is an anatomical feature of hard maple, and a knot near the top edge in the centre. The xeroradiographic images of the panel paintings showed cracks (less than 0.1 cm), voids (around 0.1 cm in diameter), vessel lines in the wooden support, and the white pigment. There appears to be two types of cracks, both less than 1 mm; one at the top edge with an increase in density (a light line) and one at the bottom edge of the painting with a loss of material (a dark line). The cracks with an increase in density were probably in the wood prior to painting and then filled up with the paint. The other cracks, which showed a decrease in density, were probably formed after the painting of the panel. The voids, approximately 0.1 cm in diameter, were filled with pigment and, therefore, now show an increase in density. The x-ray radiographs do not show the cracks as clearly. The strain gauges and wires appear on the left hand side of the image, in the centre above the roof of the painting, and on the lower right hand side above the figures.

When using the all-air coupled ultrasonic system, various sections of the poplar panel were analysed. Pieces of lead tape were placed onto the sample to give a reference for the analysis. The signal is greater over areas where the beam is not skewed by the grain of the wood. Distinct decreases in signal occur over the solitary holes and over the pieces of lead tape, whereas gradual decreases correspond to changes in grain. Over areas with many voids of different diameters and depths, the signal is smaller where there are larger diameter voids and less signal is permitted through, while the signal is larger where the voids are smaller and more signal is allowed through.

The all-air coupled ultrasonic system worked for the lower density of tulip poplar, but not for the higher density woods such as white oak. Only the higher density woods had cracks and therfore to evaluate these types of voids, a different system, the hybrid air-coupled/dry-coupled system, had to be used. The results (Figure 6) show a definite signal decreases around 1600-2200 mil and around 3200-3600 mil, corresponding to cracks. There is also a strong correlation between signal size and the direction of the grain. There is a larger signal over areas where the grain is perpendicular to the edge of thesample. The opposite is also true. Any analysis using ultrasound to discover flaws will have to consider grain orientation, which causes beam skewing, and any other artifacts within the wood. Resolution may be adversely affected and other information about the sample may get hidden because of speckle caused by the inhomogeneities in the wood.

Conclusions

Both techniques, the x-ray radiography and xeroradiography, detect the voids with the smallest diameter (0.15 cm), at all depths from the surface; the edge enhancement in the xeroradiograph technique does, however, make the voids more visible. The xeroradiographic results show the smallest cracks in the panels (less than 0.02 cm) which were not always clear in the x-ray radiograph. The other flaws, including knots, grain, and cutting defects, were more easily discernible with xeroradiography. This technique was able to show flaws in actual panel paintings and differentiate between the flaws that occurred before and after painting the wooden panel. Either a positive or a negative xeroradiographic image may be more useful according to what the individual researcher is used to and what the artifacts being looked for are. It is, therefore, valuable to take both images. X-ray radiography remains a more easily accessible technique, but clearly not as useful as xeroradiography.

The two ultrasonic systems have shown promising preliminary results in showing cracks that cannot be detected with x-ray radiography and xeroradiography. The conventional coupling problem has been overcome using these systems. The all-air coupled system is useful on lower density wood such as tulip poplar and distinguished voids as small as 0.15 cm in diameter. The hybrid air-coupled/dry coupled technique was able to map out the cracks of higher density woods, such as white oak. The system was able to show cracks of 0.1 cm.

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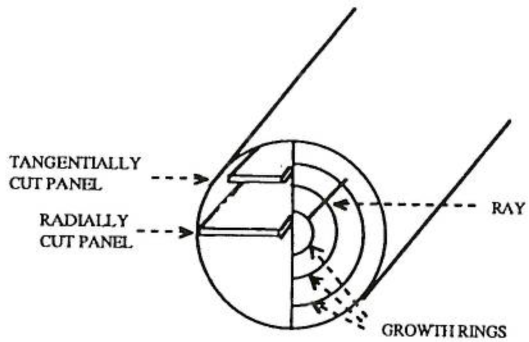


Figure 1 Cross section of wood

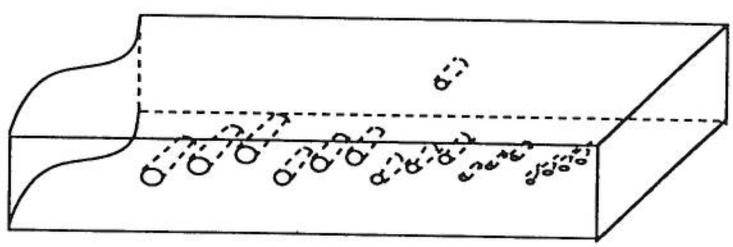


Figure 2 Angled view of wooden panel with voids

Figure 3 Panel painting: (a) photograph; (b) x-ray radiograph; and (c) xeroradiograph.

Figure 4 Panel of hard maple: (a) x-ray radiograph; (b) positive xeroradiograph; and (c) negative xeroradiograph.

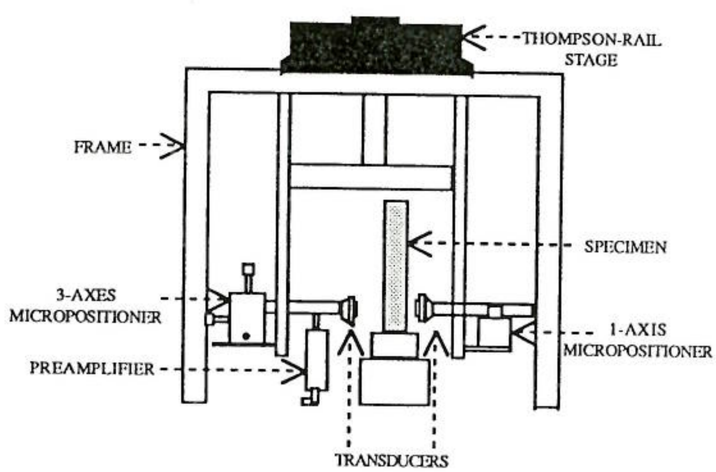


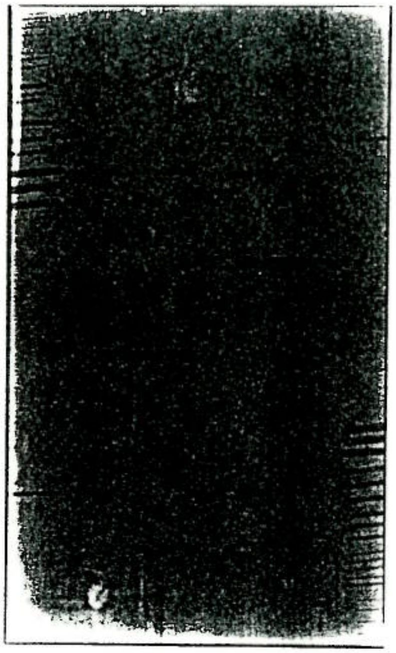
Figure 5 Experimental configuration of all-air coupled ultrasound.

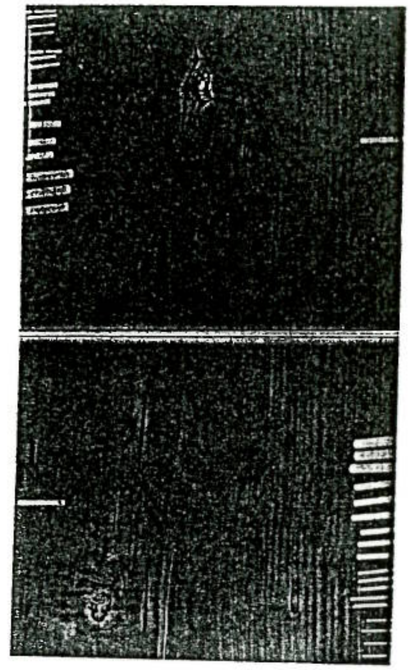
Figure 6 Results from hybrid air-coupled/dry-coupled through-transmission ultrasonic technique performed on white oak.

↖ 3a

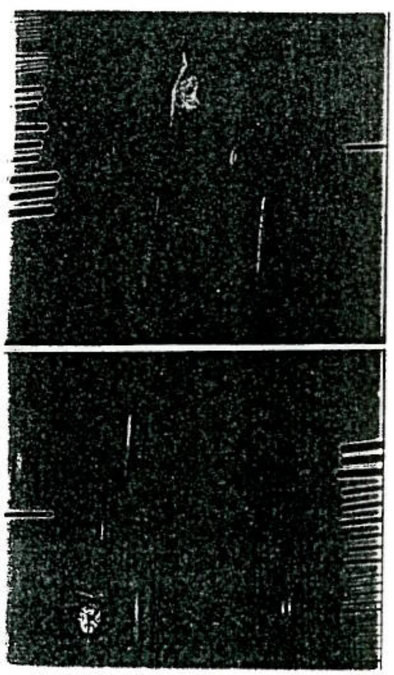
3b ↑

← 3c

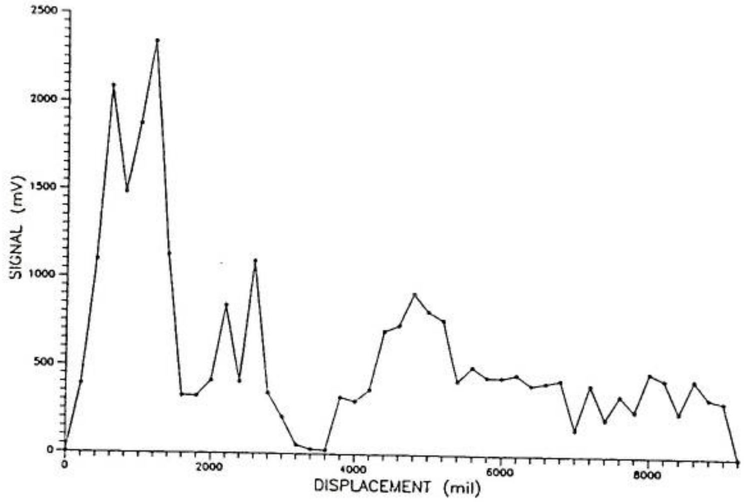




↖4a ↑4b



← 4c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2000
1500
1000
500
0
SIGNAL (mV)
0
2000
4000
6000
8000
DISPLACEMENT (mil)