A study to ascertain the viability of ultrasonic nondestructive testing to determine the mechanical characteristics of wood/agricultural hardboards with soybean based adhesives

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This manuscript is dedicated to my loving grandparents in heaven:

Mr. and Mrs. U.S. Colen, Sr.
and
Elder and Mrs. O.N. Dennis, Sr.

I am eternally grateful to these four individuals. Without their fortitude, sacrifice and guidance, this educational achievement would not have been possible. Even though they are not here to celebrate with me in body, I will celebrate with them in my soul.

With all my love and respect, I dedicate this dissertation to them.

Charles R. Colen, Jr.

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ABSTRACT

There have been numerous studies with ultrasonic nondestructive testing and wood fiber composites. The problem of the study was to ascertain whether ultrasonic nondestructive testing can be used in place of destructive testing to obtain the modulus of elasticity (MOE) of the wood/agricultural material with comparable results. The uniqueness of this research is that it addressed the type of content (constalks and switchgrass) being used with the wood fibers and the type of adhesives (soybean-based) associated with the production of these composite materials.

Two research questions were addressed in the study. The major objective was to determine if one can predict the destructive test MOE value based on the nondestructive test MOE value. The population of the study was wood/agricultural fiberboards made from wood fibers. cornstalks. and switchgrass bonded together with soybean-based. urea-formaldehyde. and phenol-formaldehyde adhesives.

Correlational analysis was used to determine if there was a relationship between the two tests. Regression analysis was performed to determine a prediction equation for the destructive test MOE value. Data were collected on both procedures using ultrasonic nondestructing testing and 3-point destructive testing.

The results produced a simple linear regression model for this study which was adequate in the prediction of destructive MOE values if the nondestructive MOE value is known. An approximation very close to the entire error in the model equation was explained from the destructive test MOE values for the composites. The nondestructive MOE values

used to produce a linear regression model explained 83% of the variability in the destructive test MOE values. The study also showed that, for the particular destructive test values obtained with the equipment used, the model associated with the study is as good as it could be due to the variability in the results from the destructive tests.

In this study, an ultrasonic signal was used to determine the MOE values on nondestructive tests. Future research studies could use the same or other hardboards to examine how the resins affect the ultrasonic signal.

CHAPTER I. INTRODUCTION

The desired possibility of examining materials without destroying them using ultrasonics originated in the late 1920s and early 1930s in Germany by Mulhauser, Trost, and Pohlman, and at the same time in Russia by Sokoloff, all of whom investigated various continuous wave techniques (Green, Jr., 1991). Developments since the 1930s have made ultrasonics one of the most versatile techniques in the nondestructive arena (Ensminger, 1988). Most nondestructive testing techniques involve low-intensity ultrasonic energy (Ensminger 1988). The through-transmission method was one of the first techniques of ultrasonic testing (Green, Jr., 1991) and the basis for discontinuity detection equipment.

During the 1940s, an American named Firestone invented an apparatus using pulsed ultrasonic wave trains to obtain reflections from minute discontinuities (Green, Jr., 1991). With this development, the use of ultrasonics along with the aid of the contemporary growth of electronic instrumentation and technology led to the marketing of practical ultrasonic waves for nondestructive testing with their primary use in metallurgical research (Green, Jr., 1991). As examination procedures improved and different materials were being exposed to new testing procedures with success, a need became apparent for determining the strength of wood and wood-based composite boards for the construction industry.

Nondestructive testing machines capable of measuring the strength of lumber came into use in the early 1960s (Pellerin, 1965). "With increasing demand, wood is now recognized as the material of choice for years to come. Ultrasound has been used to grade the materials strength properties of structural timber. This has promoted many new projects regarding the investigation and development of new techniques for the assessment of wood and wood based composite products" (Diederichs. 1998). One such product exists in the Forestry Department at Iowa State University. Ames. Iowa U.S.A., where hardboards and medium-density fiberboards were developed by using different amounts of cornstalk. switchgrass. and wood fibers bonded with synthetic resins and soy protein. The characterization of the modulus of elasticity (MOE) of this material by using ultrasonic nondestructive testing is the focus of this study.

Hoadley (1980) stated: "...the mechanics of materials is in itself a complex field of science. even for 'simple' materials that are homogeneous (uniform in composition) and isotropic (having equal properties in all directions). like steel. But on top of that, wood is an anisotropic heterogeneous material. subject to species differences, biological variability and a wide array of natural irregularities and defects" (p. 107).

Singh and Davies (1991) addressed the use of ultrasonic nondestructive testing methods for two purposes: (a) the detection and characterization of discontinuities in materials. and (b) the evaluation of material properties. A single ultrasonic transducer can be used for pulse echo tests. but this technique has several limitations such as (1) poor signal - to-noise ratios in highly attenuative materials, (2) limited discontinuity indication and characterization capabilities. (3) inability to detect all discontinuities because of component geometry. and (4) a generally slow test procedure (Singh & Davies, 1991). By using more than one transducer. the previously mentioned disadvantages can be reduced (Singh & Davies. 1991).

The current experiment was designed to investigate the use of ultrasonic nondestructive testing to determine the MOE of wood/agricultural hardboards. The examination of this material contributes to the need of evaluating how ultrasonic NDT can be used to measure characteristics and assist in the production of these composites. Exploration into the viability of using a test method that allows for continued use of the material beyond strength characterization was a major factor in the necessity of this study, because all previous evaluation of the hardboards had been done in a destructive manner. The uniqueness of this research was the nondestructive analysis of the type of composite content (cornstalks and switchgrass) being used with the wood fibers, and the type of adhesives (soybean-based) associated with the production of these composite materials.

Problem of the Study

The problem of this study was to ascertain whether ultrasonic nondestructive evaluation could be used in place of destructive testing to obtain the modulus of elasticity (MOE) of the wood/agricultural material with comparable results.

Purpose of the Study

The purpose of the study was to determine the MOE of a wood/agricultural material without the destruction of the material, and to determine the viability of using ultrasonic nondestructive evaluation to determine the MOE of a wood/agricultural material. Present methods used to test the MOE of the wood/agricultural product usually requires the destruction of the material upon evaluation. This study identified wave transmission data characteristics for the wood/agricultural materials while maintaining the material in a usable state.

Need for the Study

The need of the study was to develop a method of determining the MOE of a wood/agricultural material without destroying the samples in the process of the evaluation. Additional needs for the study include the following:

1. Maintain productive use of the wood/agricultural hardboards after its MOE (strength characteristics) have been evaluated;
2. Determine if there is damage to the samples in real-time without removal, of the samples from the manufacturing process;
3. Assist in the quality of the production of the wood-based material by implementing an online evaluation during the production process.

Research Questions

The following research questions were investigated:

1. Is there a relationship between the MOE results of the wood/agricultural material measured using a destructive test and the MOE results of the wood/agricultural material using a nondestructive test?
2. Can one predict the destructive test MOE value when the nondestructive MOE value is known?

Statistical Hypotheses

The following hypotheses were formulated to answer the research questions:

1. There is no relationship between the MOE results of the wood/agricultural material measured using a destructive test and the MOE results of the wood/agricultural material using a nondestructive test where ρ is the correlation coefficient value.

   H_o: $\rho = 0$

   H_A: $\rho \neq 0$

2. The destructive test MOE value of wood/agricultural hardboards can be predicted when the nondestructive test MOE value of wood/agricultural hardboards is known.
3. There is no significance for the model parameters.

   H_o: $\beta_1 = 0$

   H_a: $\beta_1 \neq 0$

Assumptions of the Study

The assumptions that were made include the following:

1. Error will be random.
2. The wood/agricultural hardboard composite samples for both evaluation methods will be made by using the same controlled process.

Limitations of the Study

This research was subjected to the following limitations:

1. The wood/agricultural hardboards samples are as uniform as possible from the production of the materials used.

2. The inferences made from this study are limited to the tested population of the wood/agricultural hardboards (wood fibers, cornstalks, switchgrass, and formaldehyde or soybean-based adhesives) .

Procedures of the Study

The following procedures were conducted to carry out this research:

1. Determine the research questions.
2. Review the literature related to ultrasonic nondestructive evaluation on wood/agricultural hardboards.
3. Review the Laminated Plate Wave Analyzer (LPWA) software package for its appropriateness for use in this study.
4. Determine hypotheses and statistical procedures.
5. Determine the appropriate data needed to answer the research questions.
6. Specify the sample design and the composition of various wood/agricultural hardboards to be produced by the Forestry Department.
7. Collect data using nondestructive testing of wood-agricultural hardboards.
8. Conduct a destructive test pilot study on one-half of the sample boards to determine whether to proceed with the full study before all the samples are destroyed.
9. Analyze the data from the pilot study to determine the relationships between the two MOE tests.
10. Complete the destructive data collection.
11. Analyze the data.

12. Report the findings.

13. Summarize and draw conclusions.

14. Identify future research needs.

Definition of Terms

The following terms were defined for use in this study:

Background noise – Extraneous signals caused by signal sources within the ultrasonic testing system, including the material in test.

Compressional wave – Waves in which the particle motion or vibration is in the same direction as the propagated wave (longitudinal wave).

Contact testing – A method of testing in which the transducer contacts the test surface, either directly or through a thin layer of couplant.

Decibel – The logarithmic expression of a ratio of two amplitudes or intensities of acoustic energy.

Effective penetration – The maximum depth in a material at which the ultrasonic transmission is sufficient for proper detection of discontinuities.

Frequency – The number of complete cycles of a wave motion passing a given point in a unit time (1 second): number of times a vibration is repeated at the same point in the same direction per unit time.

Impedance (acoustic) – Resistance to flow of ultrasonic energy in a medium. Impedance is a product of particle velocity and material density.

Initial pulse – The first indication that may appear on the screen. This indication represents the emission of ultrasonic energy from the crystal face.

Longitudinal wave velocity – The unit speed of propagation of a longitudinal (compressional wave).

Modulus of elasticity – The ratio of stress to strain for a given piece of wood within the elastic range (MOE or E).

Nondestructive testing – The testing to detect internal, surface and concealed defects or flaws in materials using techniques that do not damage or destroy the items being tested.

Pulse Echo Method – A single crystal ultrasonic test method that both generates ultrasonic pulses and receives the return echo.

Pulse Length – Time duration of the pulse from the search unit.

Pulse Method – An ultrasonic test method using equipment which transmits a series of pulses separated by a constant period of time (i.e. energy is not sent out continuously).

Pulse Rate – Number of pulses transmitted in a unit time (also called pulse repetition rate).

Resonance Frequency – The frequency at which a body will vibrate freely after being set in motion by some outside force.

Surface Waves – Waves that are constrained to travel along the surface of a solid or fluid interface. Their energy is concentrated in a relatively small region about one wavelength deep near the surface.

Through transmission – A test method using two transducers in which the ultrasonic vibration is emitted by one and received by another on the opposite side of the part. The ratio of the magnitudes of vibration transmitted and received is used as the criterion of soundness.

Transducer – An assembly consisting basically of a housing, piezoelectric element, backing material, wear plate (optional) and electrical leads for converting electrical impulses into mechanical energy.

Ultrasonic spectrum – The frequency span of elastic waves greater than the highest audible frequency, generally regarded as being higher than 2.0×10^4 cycles per second (cps), to approximately 10^9 cps.

Ultrasonic evaluation – A nondestructive method of inspecting materials by the use of high frequency sound waves into or through them.

CHAPTER II. REVIEW OF LITERATURE

Nondestructive testing (NDT) is the method of testing to detect internal, surface, and concealed defects or flaws in materials using techniques that do not damage or destroy the items being tested (Hayward, 1978). There is a great deal of interest in nondestructive technologies beyond the location and identification of cracks and voids. Specifically, there is a growing interest in the application of nondestructive evaluation (NDE) which entails the measurement of physical and mechanical properties of materials (Ruud, Bussiere, & Green, Jr., 1991). This measurement of material properties is often used to characterize the samples being investigated. Society's push toward higher quality products and recycling of materials provides the area of nondestructive testing with a vital role. This method of evaluation supports the attitude of maintaining our environment. The materials being evaluated in this study utilizes some products from the environment which usually are discarded and replaces carcinogenic materials.

Reis et al. (1990) stated that the feasibility of nondestructive evaluation/characterization of laminated wood products has significant economic ramifications. Destructive methods of testing require that the performance of a sample be evaluated in order to characterize the larger group represented by the sample. If destructive methods were conducted on the entire population, there would not be any product remaining for use. Analytical ultrasonics implies the measurement of material microstructure and associated factors that govern mechanical properties and dynamic responses.

Historical Overview of Ultrasonic Nondestructive Testing

The concepts of nondestructive testing have been used almost exclusively for detecting macroscopic discontinuities in structures after they have been in service for some time. It has become increasingly evident that it is practical and cost effective to expand the role of nondestructive testing to include all aspects of materials production (Green, Jr., 1991).

Interpretations of nondestructive testing (NDT) methods have been categorized as a field of study associated with the analysis, inspection, characterization or examination of an object or system to determine its future utilization without altering the physical characteristics of the test material (Ness,1995). This area of study supports society's need of reducing refuse in the environment by eliminating the waste often associated with destructive evaluation of material. Numerous ways of interrogating materials with different forms of energy exist within the destructive test arena. Destructive examination includes cutting samples from material, load testing, hardness testing and impact evaluation. All of these methods change the state of the material being tested. The destruction of material also leads to disposal decisions of the evaluated piece, which adds to the process of destructive testing.

Nondestructive methods include mechanical, visual, penetrant, thermal, optical, electrical, magnetic, radiographic, acoustic and ultrasonics testing. The particular method used is often determined by the type of material and evaluation needed. This field of study includes crack and material identification and characterization. The characterization of the microstructure of the materials (e.g., resin curing, case hardening, and stress) is the direction of new applications for NDT. The current study utilizes the capabilities of ultrasonic NDT to evaluate the wood/agricultural boards. The decision to use ultrasonic testing was determined by a report from (Green. Jr.. 1991). Ultrasonic waves are mechanical vibrations and therefore ultrasonic testing is especially suited to detection of elastic anomalies and measurement of physical properties such as porosity. structure and elastic constants (Green, Jr., 1991).

Advantages of ultrasonic NDT include the sensitivity, directivity of the signal. safety factors. and proved established applications of the method. The resolution (sensitivity) and small divergence of the signal provide critical analysis. The convenience of ultrasonics. which includes factors such as portability of the equipment, clear cut usage techniques and acceptance in industry. make it a feasible choice for material characterization.

Disadvantages associated with ultrasonic NDT procedures can exist with the coupling of the transducers or attenuation of the signal. The type and dimensions of the object determines whether the limitations of ultrasonic testing would prevent the researcher from using ultrasonic NDT as a viable method.

Ultrasonics is a branch of acoustics dealing with frequencies generally beyond the audible limit. Ultrasonic frequencies range from 25 kHz to 100 GHz. Appendix A displays a frequency spectrum and frequency range for various applications of ultrasonic testing. Frederick (1965) reported that ultrasonic energy applications are classified by either mechanical work (e.g.. welding. drilling. or physical therapy) or producing and detecting an ultrasonic signal to measure physical characteristics.

Ultrasonic techniques are important and are a valuable asset in the evaluation of microstructures. mechanical properties and discontinuities. Green, Jr. (1991) reported on some of the benefits and drawbacks of ultrasonic testing. The benefits include high sensitivity, good penetrating power. accuracy in the measurement of discontinuity size and position, fast response and need for access to only one surface of the test object. The drawbacks include inconvenience of test object geometry and internal structure. The use of ultrasonic methods in NDT are categorized into resonance, pulse, and acoustic emission (Ensminger, 1988). The resonance method consists of determining the intrinsic frequency of the object being examined. The pulse method involves the material being subjected to an ultrasonic wave. The acoustic emission method detects the ultrasonic signal emitted from the material, after some external stimuli.

The theory of sound reported by Lord Rayleigh, a famous acoustician, made some of the earliest contributions to the field of ultrasonics (Graff, 1991). Rayleigh was responsible for the modern ultrasonic transducer's principle operation. Other researchers who worked in the area with Lord Rayleigh included Colladon, Sturnm, Stokes, Lebedev, and Joule (Graff, 1991). These individuals made various contributions to the acoustic field, which was the forerunner to ultrasonics. Some of the discoveries and inventions included underwater sound velocity, theoretical expressions for sound velocity, a high frequency generator, magnetostriction, and piezoelectricity. The latter two scientific breakthroughs (magnetostriction and piezoelectricity) are the basics of electrical to mechanical transduction.

Savart, Galton, and Koenig were other early scholars of high frequency acoustics (Frederick, 1965). Their studies date back to the 1840s-1950s. Other early scientists studying the characteristics of these acoustic signals included Sokolov (1929) in Russia, Trost, Gotz, Pohlmand and Mulhauser (1930) in Germany, Sproule (1940) in England, and Firestone (1940) in the United States (Graff, 1991). These individuals made significant contributions to the field.

The application of sonar and radar to produce a minisonar for material inspection was the focus of researchers in the 1930s and 1940s (Bond, Punjani, & Saffari, 1984). This era developed the field known as ultrasonics and was recognized as an important branch of acoustics research. Early applications included discontinuity detectors, metallurgy laboratory analysis, railway axles testing, and jet engine rotor forgings manufacturing. The discontinuity detection applications had limitations associated with this method which included attenuation in some materials (Graff, 1991).

The application of ultrasonic NDT was best adapted for homogeneous isotropic materials, but has also found many uses in the heterogeneous anisotropic arena of composite materials. Thomas (1998) stated that ultrasonics was often applied to detect thickness and search for flaws in metals (e.g., cracks, voids, etc.). However, ultrasonics can also be used to ascertain grain size, measure residual stress, analyze surface characteristics, evaluate bond quality (e.g., adhesives), and determine elastic moduli.

There are two basic techniques of ultrasonic testing: (1) the through transmission technique where the energy is transmitted through the specimen being tested and the transferred energy is measured; and (2) the pulse echo technique where observation of energy reflected from flaws, cracks or voids is used to characterize the test material. The essential equipment of ultrasonic testing includes an ultrasonic probe and an 'ultrasonic flaw detector' (Bowker & Owens, 1984). Later reports by Green, Jr. (1991) referred to the basic ultrasonic test system make-up as a transmitting transducer, couplant to transfer acoustic energy to the material being tested, test material, and couplant to transfer acoustic energy to the receiver transducer. Green also noted that the selection of equipment is dependent upon the application.

The applications for ultrasonic nondestructive testing have vastly increased since its inception in the early 1930s when the technique was mainly used for discontinuities. The principal applications have expanded to include: (1) surface motion; (2) thickness measurement; (3) determination of elastic moduli; (4) study of metallurgical structure; (5) evaluation of the effect of processing variables on the component; and (6) thermoelastic analysis.

Sokolov and Mulhauser are recognized as the fathers of ultrasonic nondestructive testing from the perspective of applying the techniques to practical use (Graff, 1991). With Mulhauser obtaining the first patent of a discontinuity detector and Sokolov's concept of through transmission which showed that discontinuities would screen some of the energy from the receiver transducer (Graff, 1991). In an earlier study Altberg designed an instrument to detect ultrasonic waves (Frederick, 1965). The unique factor of the studies conducted by Sokolov was the continuous ultrasonic wave. In 1937, Sokolov developed an ultrasonic image tube based on the piezoelectric effect, which earned him the first patent granted in the United States for this type of testing (Graff, 1991).

The ultrasonic pulse echo concepts were inspired by attacks on submarines in World War II. Developments by Firestone and Sproule implemented the use of the pulse echo method. Firestone received a patent on his instrument called the reflectoscope. Sproule utilized two transducers (transmitter and receiver) to apply the pulse echo method. The difference of using two transducers was the defining characteristic of the research in England.

Kruse in Germany had also developed a discontinuity detector along with contributions to the field by Pohlman and Hiedemann (Graff, 1991).

The utilization of the pulse echo method for nondestructive testing increased dramatically after these developments. Sperry Products in the United States and Kelvin and Hughes Limited in England marketed the pulse echo nondestructive equipment developed by Firestone and Sproule. By 1955 the pulse echo method was the dominant ultrasonic technique (Graff, 1991).

The technique of ultrasonic NDT is adaptable to diversified applications. Uses for ultrasonic NDT can be applied to materials to obtain informative results of material integrity mechanical characteristics. NDT concentrates on the performance of the material, and determines if flaws or faulty characteristics exist.

Nondestructive Testing of Wood and Wood Composites

"Throughout history, man has found increasing usefulness for one of nature's commonly occurring materials—wood. The number of forms in which this material has served him is indeed vast. The useful life of wood, however, has often been limited by the failure of some component after an interval of time as a crack, or cracks, propagated through it" (Drouillard, 1990, p. 157). The many uses of wood have also spurred the technological need for more understanding of the mechanical properties of this material. Drouillard (1990) also quoted Robert L. Young's perspective on the utilization of wood: "… in the development of nondestructive testing for wood and wood-based products, specific properties need not necessarily be measured with the thought of providing an exact value for each piece tested, but rather to classify individual pieces into categories within which it could be with reasonable certainty that a definite percentage of the pieces would be within established levels" (p. 158).

The concepts of nondestructive testing of wood were formalized first by the work done by Polatch Forest, Inc. (PFI) and Jayne at Yale University (Pellerin, 1978). In 1959, PFI published results relating MOE, a measure of the stiffness of a wood specimen and MOR, a measure of the failure point of a wood specimen. The importance of this relationship was accentuated by the work done by Jayne, first at Yale University and later at Washington State University, in developing a vibration technique by which the MOE of wood could be determined (Jayne, 1959). Based on Jayne's work, commercial stress-grading equipment was developed to determine MOE and then using the PFI relationship to determine MOR (Pellerin, 1965).

A parallel line of research by Pellerin and Kaiserlik (1975) and Pellerin and Kern (1974) resulted in a new technique which measures the transmission time of a stress wave through a piece of wood. This transmission time was found to be highly correlated with mechanical properties of the wood specimen (i.e., a fast transmission time implies a specimen with high mechanical properties and a slow transmission time, a specimen with low mechanical properties) (Pellerin, 1974). Pellerin (1978) also reported the longitudinal stress wave formula used to compute the mechanical property of MOE as:

$MOE = c^2 \rho$, where:

c = transmission velocity of a wave through a wood specimen

ρ = density of the wood specimen

Ross and Vogt (1985) discussed that one-dimensional stress wave theory in homogeneous, isotropic, prismatic rod is a function of the rod's dynamic MOE and density. The equation was derived for an idealized one-dimensional case, but has been shown to exist for actual three-dimensional members so long as the length of the wave is large relative to members' lateral dimensions. As previously mentioned, wood does not possess the characteristics of homogeneality nor is it isotropic. Another study by Bertholf (1965) proved this theory was applicable to wood.

Hoyle, Jr. and Pellerin (1978) studied the stress waves in wood barrel arches in two school buildings. They used stress wave technology to study glued laminated wood sections in which known built in void areas of different sizes and configurations were studied. Out of this study they found the void areas caused a reduction in the velocity of the stress wave that was characteristic of the size and shape of the void.

Kennedy (1978) reported the two basic methods of nondestructive testing of wood products were resonant and velocity testing of which practical applications of ultrasonics favored the pulse velocity techniques. Techniques for using ultrasonics in the production of panel products were reported by Baker and Carlson (1978). Inspection of wood panels during the production may enhance the quality of the product. Baker and Carlson (1978) developed instrumentation to monitor wood composite production nondestructively.

The possibility of detecting fracture phenomena in wood in the early stages was studied by Bucur (1978). Gasick, Lemaster, and Dornfeld (1987) studied the type of transducer pulse-receiver combinations that would produce the optimal results for NDT of wood composites. Portala and Ciccotelli (1989) reported on the evaluation of wood characteristics using sensors to measure three types of attributes: (1) measurement of external dimensions: (2) inspection of appearance; and (3) nondestructive internal inspection. Portala and Ciccotelli's (1989) study focused on defining sensors that could characterize wood in real-time.

Another aspect of ultrasonic nondestructive testing of wood was examined by Szabo (1978) who reported on composite board analysis and studied the basic parameters associated with executing the test. Pellerin and Morschauser (1973) worked with particleboard to predict flexural behavior.

The evaluation of characteristics of wood-based composites was studied by Ross and Pellerin (1988) using longitudinal stress waves. The characteristics examined included tensile, flexural, and internal bond properties of the materials. Results from their study showed a strong correlation between stress wave speed and tensile and flexural moduli but specific gravity was a poor predictor of tensile and flexural moduli.

Ross and Pellerin (1991) reported on past, present and future research in the area of ultrasonic nondestructive testing. They provided a brief overview of the evolution of NDT over the past 30 years and how future opportunities would propose welcomed challenges.

A study completed by Bozhang and Zhiyoung (1994) used a nondestructive evaluation vibration technique to predict internal bond strength, MOE, and MOR of full-sized particleboard panels. The researchers obtained high correlation coefficient results. This study examined the panels by exciting the resonance frequency within the panels and observing the vibrations within the boards. The calculation of the frequency was determined.

The current study was not dependent upon the resonance frequency of the material, because an exact frequency signal was transmitted through the hardboards.

A summary of the historical development of ultrasonic nondestructive testing, and its use with wood and wood composites was discussed. The focus of historical ultrasonic NDT studies was to compare non destructive to proven destructive test results. The field of NDT relies on destructive evaluation as the standard for test comparison.

The current study examined theory-based use of ultrasonic nondestructive testing to evaluate a different type of wood composite. The wood composite content of wood fibers, cornstalks, and switchgrass bonded together with soybean based adhesives was the distinctive characteristic of the wood composite material studied. The producers of the composite had previously only used destructive measures to evaluate the final product. The assessment of the material without destruction was the focus of this study.

CHAPTER III. METHODOLOGY

Population of the Study

The population of this study was wood/agricultural fiberboards made from wood fibers, cornstalks, and switchgrass bonded together with soybean-based, urea-formaldehyde and phenol-formaldehyde adhesives.

Sample

The samples used in the study were dry-formed hardboard samples. The specifications were made according to Kuo et al. (1998, p. 72):

> Cornstalks from central Iowa and switchgrass from southern Iowa were collected in the fall of 1994. Cornstalk and switchgrass were processed into pulp by a pressurized disk refiner at the technical center of Masonite Corporation, West Chicago, IL. Cornstalk and switchgrass fibers also were obtained by using an atmospheric Sprout-Bauer refiner at the Center for Crop Utilization Research, Iowa State University. The adhesives used were a liquid pnenol-formaldehyde (PF) resin (50% solids, pH 11.0, and 300 centipoises viscosity at 77°F) was obtained from the Georgia-Pacific Corporation, and a urea-formaldehyde (UF) resin (WC-10, 65% solids) and a wax emulsion (EW 430H) were obtained from Borden Chemical Company. Two types of soy protein isolates were used, Arpro 2100 from ADM and Supro 760 form Protein Technologies International. Arpro 2100 is in the form of fine granules that require dispersal in water or other solvents for use as an adhesive, whereas Supro 760 is a fine powder that can be used directly in a similar way as powder PF is used. The fiberboards used in this study for the samples were dry-formed hardboard smooth on both sides (S2S). The (S2S) boards were made in three wood/agricultural fiber compositions of 100/0, 50/50, and 0/100. The agricultural fibers used were pressure-refined and were bonded either with 8 percent UF or 4 percent PF plus 4 percent Supro 760. The size of the specimens were 9" × 9" × 1/8" thick S2S boards at a target density of 62.4 pcf. In the production of the dry-formed hardboard, an exact amount of furnish was hand-felted into a 9" × 9" forming box and hotpressed to 1/8" thickness.

Level of Confidence

In statistical testing, alpha (α) denotes the acceptable error rate for the test being used. Therefore, if alpha is set at .025, this means the researcher is willing to accept five false decisions out of 100 (Winer, Brown, & Michels, 1991). Alternatively, beta (β) is the power of the test to reject the null hypothesis correctly when it is false (Winer et al., 1991). A Type-I error can be made by a researcher if the null hypothesis is mistakenly rejected (Rosenberg, 1990). Alternatively, a Type-II error is made when a null hypothesis that is false is not rejected (Rosenberg, 1990). Because $\alpha = .025$ and $\beta = .025$ were used, this resulted in a 95% confidence interval.

Experimental Design

The first procedure of the experimental design was the development of the research questions. A review of literature on ultrasonic NDT and equipment for the measurements was conducted. Hypotheses and statistical procedures were determined. The design of the samples was also determined. The collection of appropriate data to answer the research questions was conducted. The first statistical procedure performed was a correlation analysis. This test allowed for the determination of the relationship between the destructive test (DT) MOE values versus the NDT MOE values between the two data sets on the wood/agricultural hardboard composites. The next step was to verify if there was a relationship between the mean MOE values for the DT and NDT methods. At this time the DT modulus of rupture (MOR) data was also obtained. DT MOR values were correlated with destructive test MOE values. A high correlation between MOR and MOE was expected.

If this correlation were low, it would prevent a nondestructive MOR prediction of wood/agricultural hardboard composites. The next step in the design was to develop a regression model consisting of an intercept and coefficients to obtain for use in predicting the DT MOE.

All the samples were tested first by using the NDT method that consisted of sending an ultrasonic signal of 100 kHz through the sample and measuring the time of travel. Following the NDT data collection, the identical hardboards were tested destructively using a Universal Testing Machine by Reihle (Kuo et al., 1998) which was retrofitted by Measurement Technologies, Incorporated (MTI) with a 40,000 pound load cell controlled by a computer program written for American Standard Measurement (ASTM D-1037). The computer software ran a three-point load test where an increasing force was placed on the sample until it failed. This information was used as the standard to which the NDT method data was compared.

After each sample failed, the MTI software package calculated the MOE and the MOR values for each of the samples. The primary reason for choosing the correlation method of design for this research was to show there was a relationship between the two types of evaluation.

Variables

The independent and uncontrolled variables of the study included the NDT and construction of the fiberboards that determined the density and the time of travel of the ultrasonic signal. An attempt was made for the hardboard samples that were produced to be uniform. and for the process to control the dimensions (e.g., same length and approximate thickness) (± .001). The makeup of the fiberboards was varied, with different percentages of wood-fiber and agricultural fiber content and the percentage adhesive used in the process. Table 3.1 illustrates how the sample content varied.

Table 3.1. Sample content for wood/agricultural hardboards

	Fiber Content Percentage			Resins/Adhesives		
Sample	Wood	Cornstalk	Switchgrass	Soy	UF	PF
159	50	50	–	6	1	6
160	50	50	–	6	–	6
165	50	50	–	9.6	–	3.6
166	50	50	–	9.6	–	3.6
175	50	–	50	9.6	2.4	–
176	50	–	50	9.6	2.4	–
191	50	50	–	70	–	30
192	50	50	–	70	–	30
195	50	50	–	70	12	30
196	50	50	–	–	12	30
199	50	50	–	–	12	–
200	50	50	–	–	12	–
203	100	–	–	–	12	–
204	100	–	–	–	12	–
207	100	–	–	70	–	30
208	100	–	–	70	–	30

Key: Soy = soy protein isolates; UF = urea-formaldehyde resin; PF = phenol-formaldehyde resin

Instrumentation

Destructive test

The destructive test instrumentation consisted of a Universal Testing Machine by Reihle which was retrofitted by Measurement Technologies, Incorporated (MTI) with a 40,000 pound load cell controlled by a computer program written for American Standard Measurement (ASTM D-1037) from the Iowa State University Forestry Department. This software package runs a 3-point Flex Test program, as diagrammed in Figure 3.1, by the following procedure: The center loading roller allows for sensing center point deflection of the specimen either by crosshead motion or by arranging a special deflection transducer to measure the local bending deformation at the center. This measures the MOE and MOR values for each sample.

Nondestructive test

The instrumentation for the NDT was furnished by the Digital Wave Corporation. Due to the manufacturer's confidentiality requirement for the instrument only a generic description was allowed for this study. The model 4100, Very Low Frequency (VLF) ultrasonic system was a low frequency ultrasonic analysis system for inspection of materials and structures. The system consisted of a function generator, low frequency continuous wave amplifier, 2 channels of wide band, digital data acquisition hardware, analog signal conditioning hardware, sensors and software analysis package as illustrated in Figure 3.2.

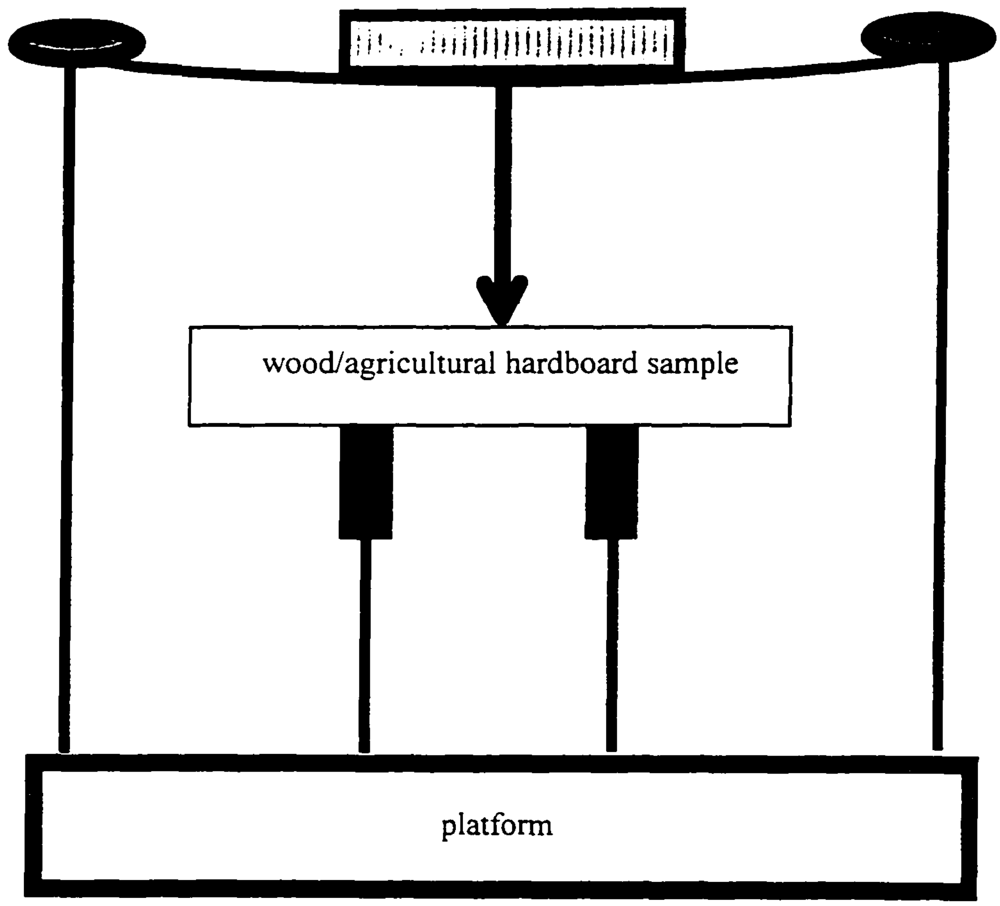

Figure 3.1. Destructive 3-point test

The G3555, 30 MHz Synthesized Function Generator produced a high quality sinusoidal waveform at a frequency of 100kHz. The sine wave minimum and maximum waveform amplitude was $10mV_{p-p}$ - $10V_{p-p}$ introduced into a 50Ω load. The sine wave accuracy at 100kHz was $\pm$ 0.2dB at $10V_{p-p}$ and $\pm$ 0.4dB at $5V_{p-p}$.

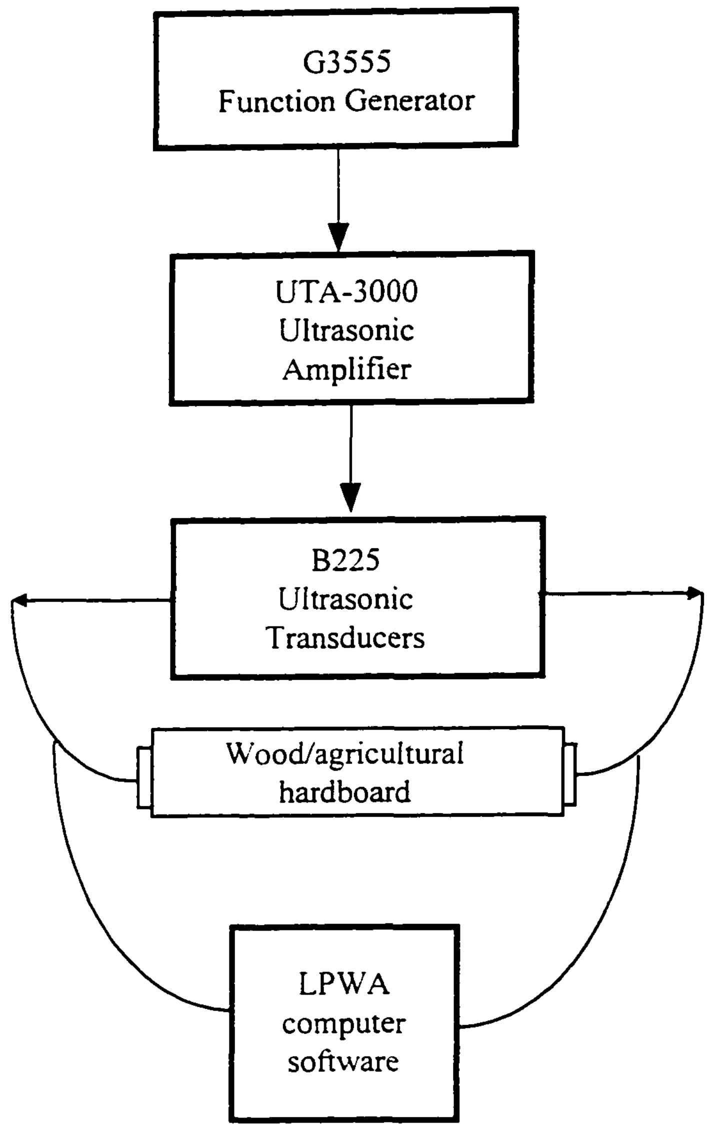

Figure 3.2. Nondestructive test instrumentation

The UTA-3000 Ultrasonic Amplifier is a high voltage, continuous wave instrument which amplifies a low amplitude RF wave from an external function generator for ultrasonic testing. The amplified output was connected to an ultrasonic transducer, used to introduce a signal into the material. The frequency range for the amplifier was 12kHz - 500kHz $\pm$ 3dB, the amplifier input maximum was $\pm 3V_{p-p}$, and the output maximum signal 2 was $600V_{p-p}$ into 1MΩ load, which was also the ultrasonic transducer impedance. The ultrasonic signal used with the transducers was 100kHz. This optimum frequency for detection of the echo pulse as the ultrasonic signal propagated through the samples was determined by observing the maximum output voltage of the signal. The software package was the Laminated Plate Wave Analyzer (LPWA) which was designed for acquisition and analysis of waveforms.

Waveforms modulated by pulsing were captured and stored digitally permitting a more detailed signal analysis than analog systems. The software package provided control for the A/D board, function generator, data acquisition and post test replay analysis and consists of four modules: (1) waveform generator; (2) data acquisition; (3) waveform analysis; and (4) materials analysis, as shown in Figure 3.3. Acquisition and post-test software were operated within DOS and Microsoft Windows™ 3.1 operating systems.

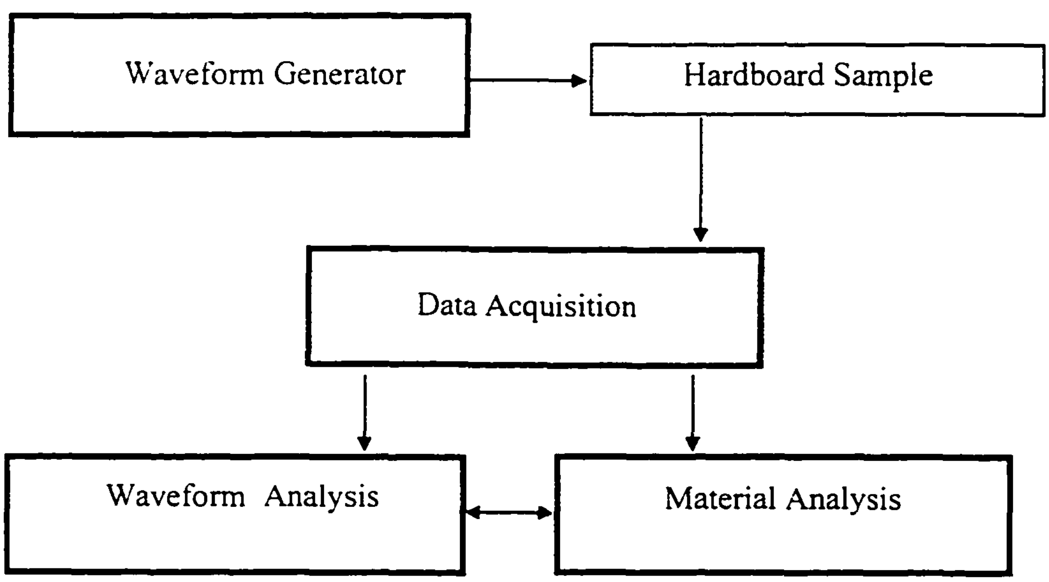

Figure 3.3. Four modules of post test replay analysis

Data Collection

Data were collected using the two different methods. First, the ultrasonic NDT was used, followed by the 3-point DT.

Nondestructive procedure

Data for the NDT were collected at the Digital Wave Corporation in Englewood, Colorado. All the instrumentation used was calibrated and maintained based on the manufacturer's recommendations in an attempt to assure data reliability. Tests were run over a three-day period on 16 wood/agricultural hardboard composites produced by the Iowa State University Forestry Department.

The hardboards were marked at a two-inch interval to denote the transducer placement (Figure 3.4). In preparation for the destructive test, the hardboards were marked into 2" size strips. The marks at each end, ¼" from each edge (after cutting), were the positions for the transducers.

The location of the transducers for data collection is shown in Figure 3.5. Each transmitting and receiving transducer was interfaced to the hardboards with glycerin as the couplant. The NDT was run on all the hardboards before the DT was administered. The content of the hardboard's construction (wood fiber and agricultural fibers content ratio along with adhesive) varied and was not known during the NDT measurements.

The data collected at the Digital Wave Corporation were the time duration of the ultrasonic wave at a frequency of 100 kHz sent through the hardboards. The investigator chose to transform this time data to a MOE value which could be correlated with the MOE

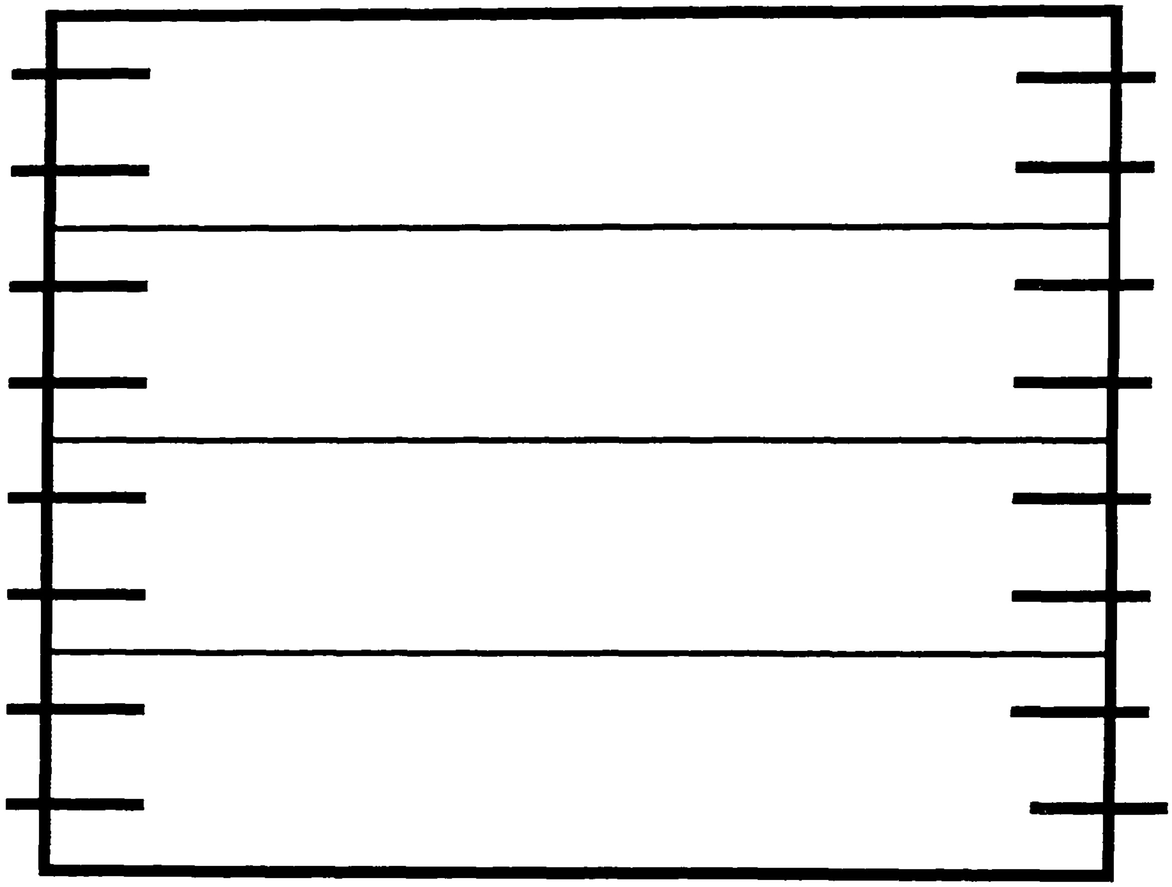

Figure 3.4. Wood-agricultural hardboard sample (9" × 9" × 1/8") marks for placement of the transducers

value from the DT. In order to calculate the MOE, the velocity and hardboard density (ρ) were needed. The calculation of the nondestructive MOE, was determined by first calculating the velocity (c) in inches/microseconds squared of the ultrasonic wave.

$$MOE = c^2 \rho,$$

c = the velocity of the wave,

ρ = the density of the hardboard sample.

$$c = L / T$$

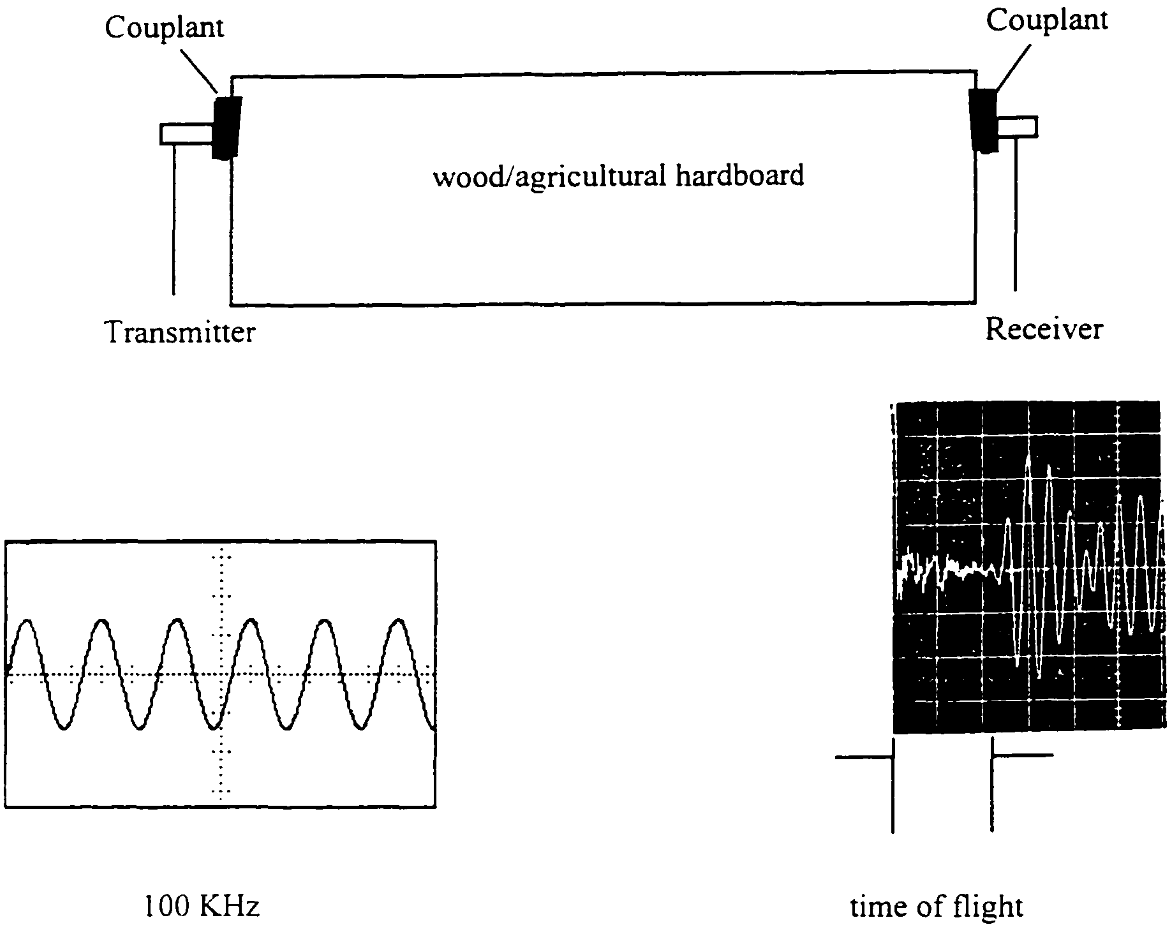

Figure 3.5. Location of transducers for ultrasonic nondestructive test

where:

L = distance of the hardboard in inches

T = the time of flight in microseconds.

The density is determined by the following formula:

$$\rho = WGT / L * W * TH * K$$

where:

WGT = weight of the hardboard sample in pounds

L = length of the hardboard sample in inches

W = width of the hardboard sample in inches

TH = thickness of the hardboard sample in inches

K = gravitational acceleration in / sec-sec,

Destructive procedure

The DT data were collected on the Iowa State University campus in the Wood Testing Laboratory located in Bessey Hall during a three-week period during November 1997. The 9" × 9" × 1/8" hardboards were cut into 2" × 4.5" pieces, (the size required for the 3-point destructive test), as shown in Figure 3.6. This resulted in 128 pieces. Four pieces were destroyed in the calibration process for the DT. Eight pieces were rescued from destruction for future nondestructive analysis (once the hardboards were destroyed no further analysis was possible).

The DT was run on the 116 hardboards. Each sample was loaded until it failed and the corresponding MOE and MOR were calculated and reported by the MTI software package

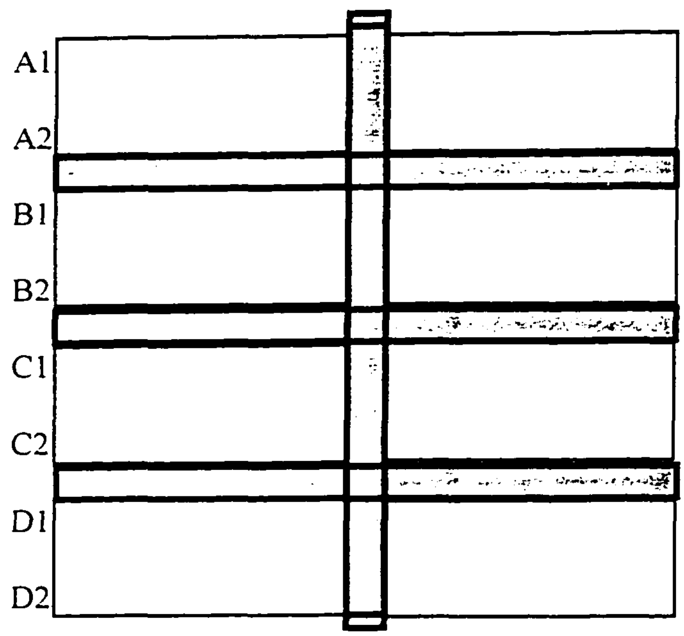

Figure 3.6. Destructive test hardboard cutting layout

Analysis

The process of analysis for this research consisted of the following procedures:

1. Determine if there was a relationship between the results of the NDT and the DT (this was obtained by correlation analysis of the two MOE values from the test);
2. Calculation of the MOE value for the NDT was conducted;
3. The nondestructive system produced the amount of time taken for the ultrasonic signal to propagate through the hardboard sample;
4. The measured time from each sample was multiplied by the density of the each hardboard sample which resulted in the MOE value for the NDT.

The DT value for the MOE was given by the Universal Testing Machine with the use of the MTI software package. The MOE results from the two tests were the data used for the various statistical analysis.

Summary

The statistics software packages that were used to analyze the data were Microsoft Excel™ (Microsoft, 1994) and Minitab™(Minitab, 1994) Microsoft Excel™ is a spreadsheet software package with some statistical analysis tools. The calculation of the MOE values completed in this study was done using this software package. The data were easily categorized and calculated with excel. Minitab for Windows is a powerful statistical software package that provides a wide range of basic and advanced data analysis capabilities. This software package was used to analyze the results of the two tests.

The following statistical procedures were employed to study the relationship between the DT and NDT methods:

1. Correlation Analysis
2. Analysis of Variance (ANOVA)
3. Linear Regression

The results of the analysis are reported in Chapter 4.

CHAPTER IV. RESULTS AND FINDINGS

The results of the statistical analysis and the significant findings from the data are discussed in this chapter. Table 4.1 illustrates the results of the MOE values for the nondestructive and destructive test for each sample. These values were derived from the formulas discussed in Chapter 3. Appendix B displays the time of flight in microseconds of the ultrasonic wave through each hardboard sample and the destructive test MOE value for each sample. The data used for the calculation of the nondestructive MOE values in Appendix C illustrate the variables and dimensions of each sample.

The analysis of the data in this study determined the results of the hypotheses and research questions. The statistical procedures employed to analyze the data were based on the needs dictated by the objective of this study. The statistical analysis revealed acceptable information for the interpretation of the values calculated. The results also provided the researcher with sufficient data to accomplish the purpose of the study.

Restatement of the Purpose

The purpose of the study was to indicate the MOE of a wood/agricultural material without the destruction of the material, and to determine the viability of using ultrasonic nondestructive evaluation to determine the MOE of a wood/agricultural material. Present methods used to test the MOE of this wood/agricultural product require the destruction of the material upon evaluation. This study identifies the mechanical properties of the wood/agricultural hardboards by wave transmission data while maintaining the material in a usable state.

Table 4.1. Results of the nondestructive test MOE and destructive test MOE

Sample	MOE-ndt (psi)	MOE-dt (psi)
159A1	312407	284881
159A2	348594	403698
159C1	319688	272006
159C2	306110	469874
195A1	338955	402657
195A2	384456	399852
195B1	402924	455843
195B2	445376	527074
195C1	412261	543375
195C2	409413	458015
195D1	401043	494647
195D2	461682	475406
199A1	446834	507178
199A2	431722	514916
199B1	447282	565417
199B2	420403	520468
199C1	412367	531574
199C2	451115	512382
199D1	432985	550342
199D2	428375	489566
166A1	291495	265253
166A2	325018	305466
166B1	284751	288726
166B2	332810	221961
166C1	307945	325348
166C2	276764	337679
166D1	304731	271660
166D2	326304	315919
176A1	155643	138624
176A2	212328	139748
176B1	268016	211447
176B2	271885	218835
176C1	313366	329614
176C2	344493	317607
176D1	376060	454440
176D2	397310	310878
203A1	459590	643371

Table 4.1. (Continued)

Sample	MOE-ndt	MOE-dt
203A2	520213	717711
203B1	456094	589540
203B2	491810	553160
203C1	480912	651606
203C2	494257	502728
203D1	508521	717240
203D2	483017	693169
208A1	425342	539931
208A2	528678	523424
208B1	502430	650347
208B2	540168	703874
208C1	524819	635949
208C2	531411	665550
208D1	474433	459914
208D2	369896	591680
160A1	329044	405707
160A2	368965	477551
160B1	405442	604237
160B2	388076	517252
160C1	414770	621788
160C2	423347	559060
160D1	413001	445748
160D2	331518	505415
165A1	502739	561083
165A2	368965	365261
165B1	418864	537213
165B2	368242	401735
165C1	338791	406142
165C2	374515	493119
165D1	376719	419328
165D2	389890	374344
175A1	273346	386808
175A2	300295	324477
175B1	313797	399304
175B2	366105	481221
175C1	380808	433953
175C2	418556	503690

Table 4.1. (Continued)

Sample	MOE-ndt	MOE-dt
175D1	418179	541599
175D2	435996	500034
191A1	515432	602978
191A2	423657	484562
191B1	472964	586885
191B2	490975	702554
191C1	476203	693402
191C2	443784	652816
191D1	457492	620006
191D2	502244	677183
192A1	505220	637299
192A2	454590	614476
192B1	499719	757145
192B2	465064	624823
192C1	490728	597210
192C2	539664	737126
192D1	536913	716674
192D2	589181	675682
196A1	413184	522320
196A2	507233	604017
196B1	539664	770356
196B2	534743	687368
196C1	579026	870580
196C2	524342	653584
196D1	508031	692711
196D2	563761	663247
200A1	559041	704385
200A2	454203	706700
200B1	477394	667195
200B2	490779	761612
200C1	481190	673480
200C2	488706	751252
200D1	480424	665763
200D2	520528	797953
204A1	550370	833954
204A2	610713	859271

Table 4.1. (Continued)

Sample	MOE-ndt	MOE-dt
204B1	574263	828442
204B2	550529	717826
204C1	514466	728996
204C2	525390	725189
204D1	512139	808721
204D2	563947	800040

Experimental Results

The nondestructive tests were completed at Digital Wave Corporation in Englewood, Colorado. The destructive test data were collected in the Forestry Department at Iowa State University, Ames, Iowa. Sixteen wood/agricultural hardboards were analyzed using the ultrasonic nondestructive testing method. The same hardboards were analyzed using the destructive testing 3-point method (ASTM D-1037) after being cut to the specified length for the test.

The correlation coefficient indicated there was a relationship between the destructive MOE values and the nondestructive MOE values. A linear regression model was developed which allowed the investigator to predict the destructive MOE value for a known nondestructive MOE value. The ANOVA indicated a value for β_1 which was not equal to zero. The probability of this occurring by chance was shown to have a P value less than 0.0000 (i.e., significance); therefore, the results of the ANOVA showed that $\beta_1 \neq 0$. The correlation analysis determined the degree of relationship of the ANOVA analysis which was found to be $R = .91$, or high, and $R^2 = .83$ which meant that 83% of the variability was explained by this model (i.e., R^2 value is a measure of the amount of reduction in the variability of Y obtained by using the regressor variables in the model).

Regression models are often fitted to data when the true functional relationship is unknown. Naturally, one would like to know whether the order of the model tentatively assumed is correct. Another test designed to check the validity of this assumption is called the Lack-of-Fit Test (Montgomery, 1991). The Lack-of-Fit test could have been done to show the variability in a more formal way. The hypotheses for the Lack-of-Fit test would have been stated as follows:

H_o: The model adequately fits the data

H_a: The model does not fit the data

From an examination of the residual plots and the regression line plot, one could accept the null hypothesis for the Lack-of-Fit test. By observing the sum of squares attributable to pure experimental error (DT) and the sum of squares attributable to the lack of fit of the model, one fails to reject the null hypothesis pertaining to the Lack of fit test. This interpretation supports the linear regression model developed for this study, assuring this is the best fit for this set of data.

Findings Related to the Hypotheses

The findings for each hypotheses in this study are presented as follows.

1. It was hypothesized there was no relationship between the MOE results of the wood/agricultural material measured using a destructive test and the MOE results of

the wood/agricultural material using a nondestructive test where ρ is the correlation coefficient value.

H_o: $\rho = 0$

H_A: $\rho \neq 0$

One can reject the null hypothesis because a value of 0.91 was obtained for the value of ρ (see Table 4.2).

2. One can predict the destructive test MOE value of wood/agricultural hardboards from the full regression model when the nondestructive test MOE value of wood/agricultural hardboards is known. The analysis showed the coefficient for the independent variable to be significant and the linear regression equation to be a good fit.

3. There is no significance for the model parameter.

   H_o: $\beta_1 = 0$

   H_A: $\beta_1 \neq 0$

   One can reject the null hypothesis because a P value less than 0.0000 was found which proved to be significant; therefore, the value of the model parameter was not equal to zero.

Table 4.2. Correlation analysis for the destructive MOE vs. nondestructive MOE

Correlation Analysis	
Multiple R	0.9117
R Square	0.8312
Adjusted R Square	0.8297
Standard Error	68,202.92
Observations	116

Findings Related to the Research Questions

Two research questions guided this study.

Research Question 1: Is there a relationship between the MOE results of the wood/agricultural material measured using a destructive test and the MOE results of the wood/agricultural material using a nondestructive test? That is, H_A*:* $\beta_1 \neq 0$*, where* β_1 *is the coefficient for a linear relationship between the between the destructive MOE values and the nondestructive MOE values*

Yes, there is a relationship between the MOE results of the wood/agricultural material measured using a destructive test and the MOE results of the wood/agricultural material using a nondestructive test. The data used to answer Research Question 1 are displayed in Table 4.1.

The correlation coefficient (R) of 0.9117 between the destructive MOE values and the nondestructive MOE values indicated a high correlation with a P-value less than 0.0000. The correlation coefficient shows that the dependent variable, destructive MOE and the independent variable nondestructive MOE is strongly correlated with an R = 0.91. The value of R^2 equals 0.83, indicating that 83 percent of the variability in Y has been explained by the predictor X_1.

The standard error value shown in Table 4.2 explains the amount of variation in the nondestructive test MOE from the actual destructive test MOE values. A residual is the difference between the observed value of the dependent variable and the value predicted by the regression line. It is important to examine the residual plots to check whether the required assumptions of linearity, normality and independence of observations are met because residuals are conceived as a measure of summary statistics such as R^2. Such summary statistics are useful in determining whether the fit of the regression equation is good or bad, and whether the explained variation is adequate.

Research Question 2: Can one predict the MOE values for destructive test when the MOE value for a nondestructive test is known?

Yes, one can predict the MOE values for destructive test when the MOE value for a nondestructive test is known. The results of Research Question 2 are displayed in Table 4.3 and the linear regression model. The results of the ANOVA revealed there was significance among the destructive test MOE values and the nondestructive test MOE values which indicated a P-value less than 0.0000 and a degree of significance given by the value of $R^2 = .83$.

Table 4.3. Results of the ANOVA procedure for the test of H_o: $\beta_1 = 0$ vs H_a: $\beta_1 \neq 0$

		ANOVA			
Source	df	SS	MS	F	P
Regression	1	2,611,030,285,955.62	2,611,030,285,955.62	561.31	0.0000
Residual	114	530,286,781,768.34	4,651,638,436.56		
Total	115	3,141,317,067,723.97			

The linear regression model is

$$Y = \beta_o + \beta_1 X_1 + \epsilon$$

β_o = the intercept of the linear regression model,

β_1 = the coefficient for the independent variable of the linear regression model,

X_1 = the independent variable,

ϵ = the random error term

Where $\hat{\beta}_o = -186{,}025.58$ and $\hat{\beta}_1 = 1.6680$.

$$\hat{Y} = \hat{\beta}_o + \hat{\beta}_1 X_1.$$

$$Y = -186{,}025.58 + 1.668\ X_1$$

This equation is adequate because it conforms to the assumptions and predicts well. The assumptions are supported by the normality plot in Figure 4.1, and the residual plots in Figure 4.2 and Figure 4.3. The regression plot in Figure 4.4 displays the fitted regression line of the data for NDT values placed into the linear regression formula. Figure 4.5 displays the fitted regression line, 95% confidence intervals (CI), and 95% prediction intervals (PI). A confidence interval refers to a parameter, or population characteristic, whose known value is fixed but unknown to us. In contrast, a future value of Y is not a parameter but instead a random variable; for this reason one refers to an interval of plausible values for a future Y as a prediction interval (Devore, 1987).

Eighty-three percent of the variance is explained by the model and the value of the standard error from Table 4.1 is close to the variance within piece of the destructive test MOE data. The value of the standard error is 68,203 and the value for the variance within piece is 72,216. The comparison of these two values illustrates that, for this particular set of data, the linear regression equation is the best model to predict destructive MOE from nondestructive MOE.

One may consider if a better prediction can be made for the destructive test MOE value when the nondestructive test MOE value is known with this study. However, a better prediction cannot be made for the destructive test MOE value when the nondestructive test

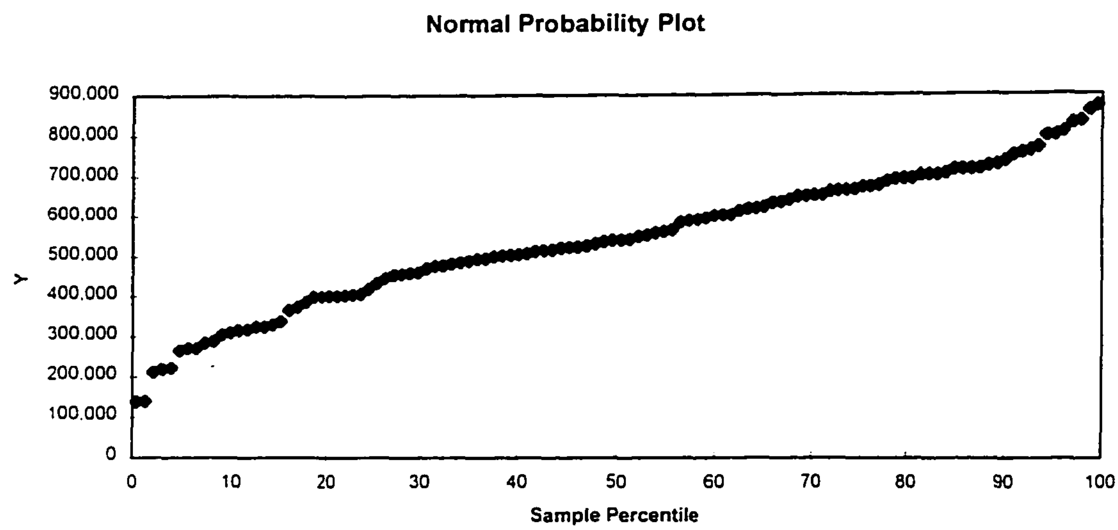

Figure 4.1. Normal probability plots of the destructive test MOE

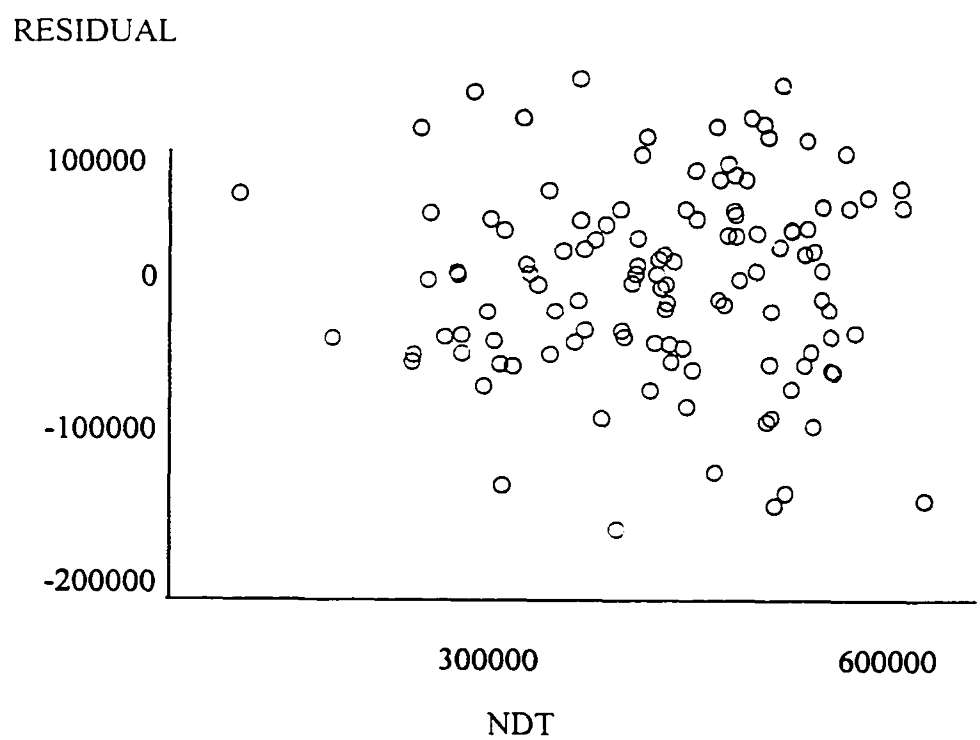

Figure 4.2. Residuals plot of NDT

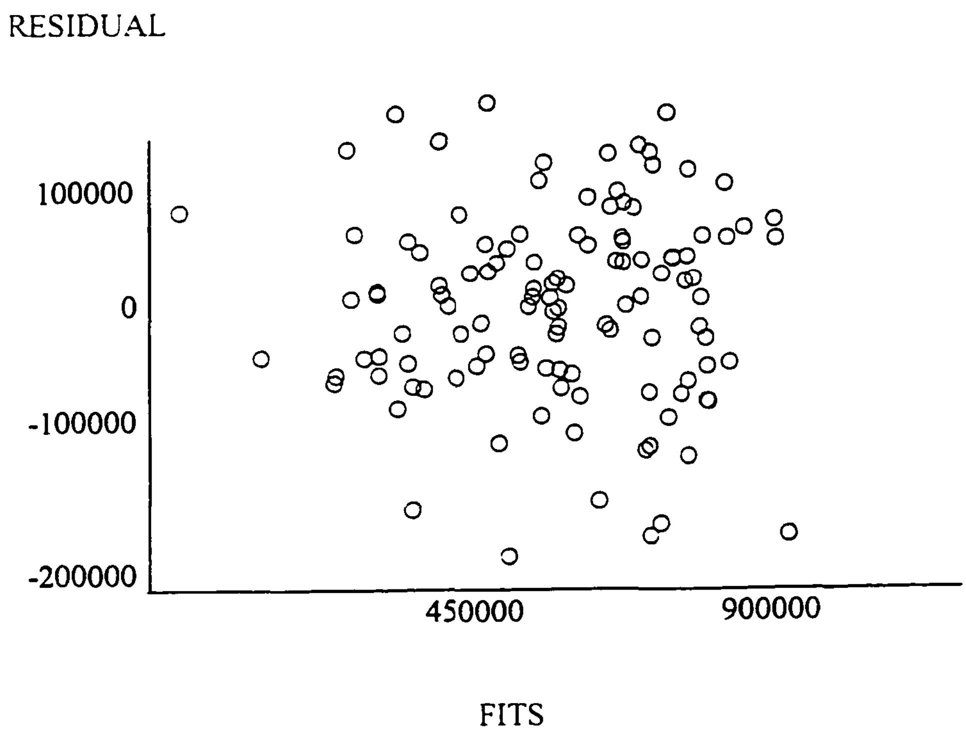

Figure 4.3. Residuals plot of the fitted data

MOE value is known because all of the variation is explained by the linear regression model. This prediction is also supported by the comparison of values of the within piece variation of each sample versus the standard error of the regression model. Another consideration is the potential for improvement of the existing linear regression model. The only way to improve the model is to reduce the variance introduced by the destructive test equipment.

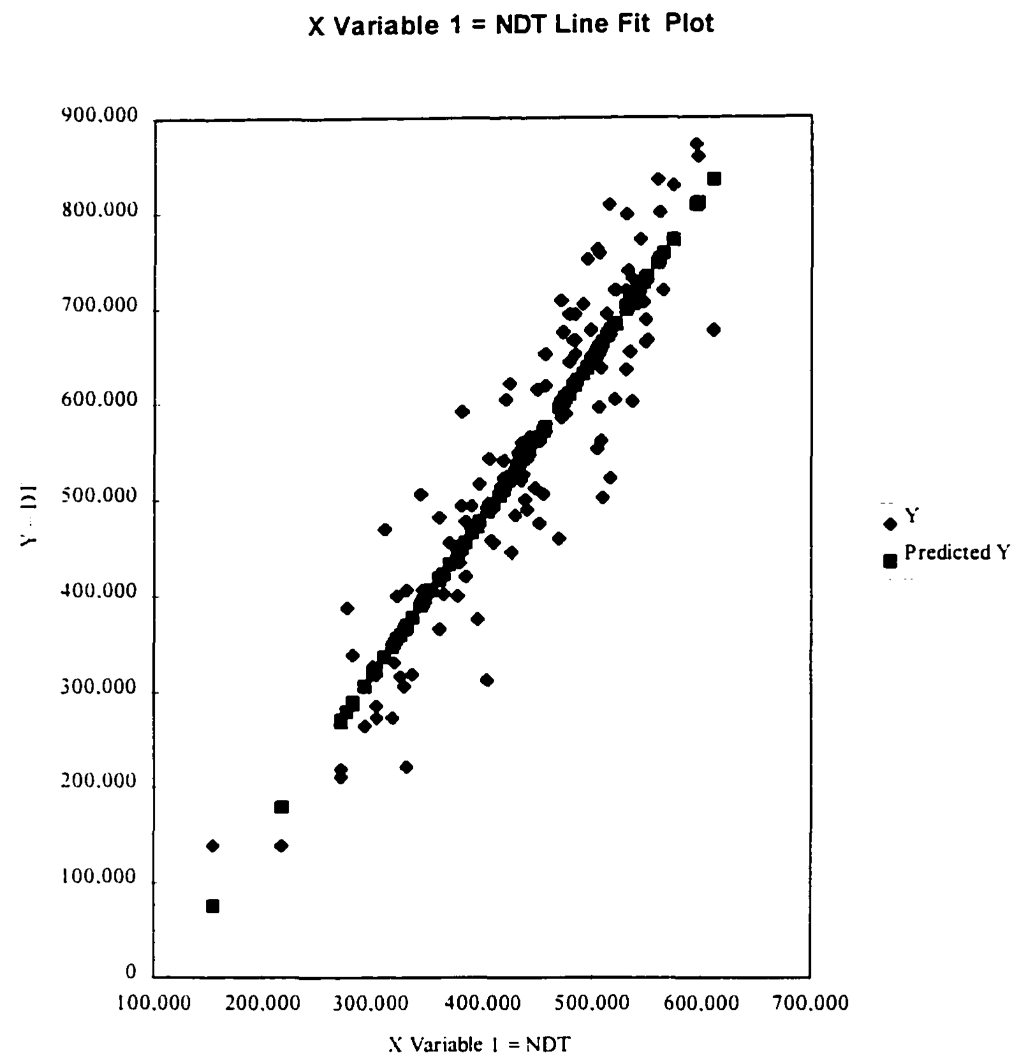

Figure 4.4. The data when NDT values are placed into the linear model

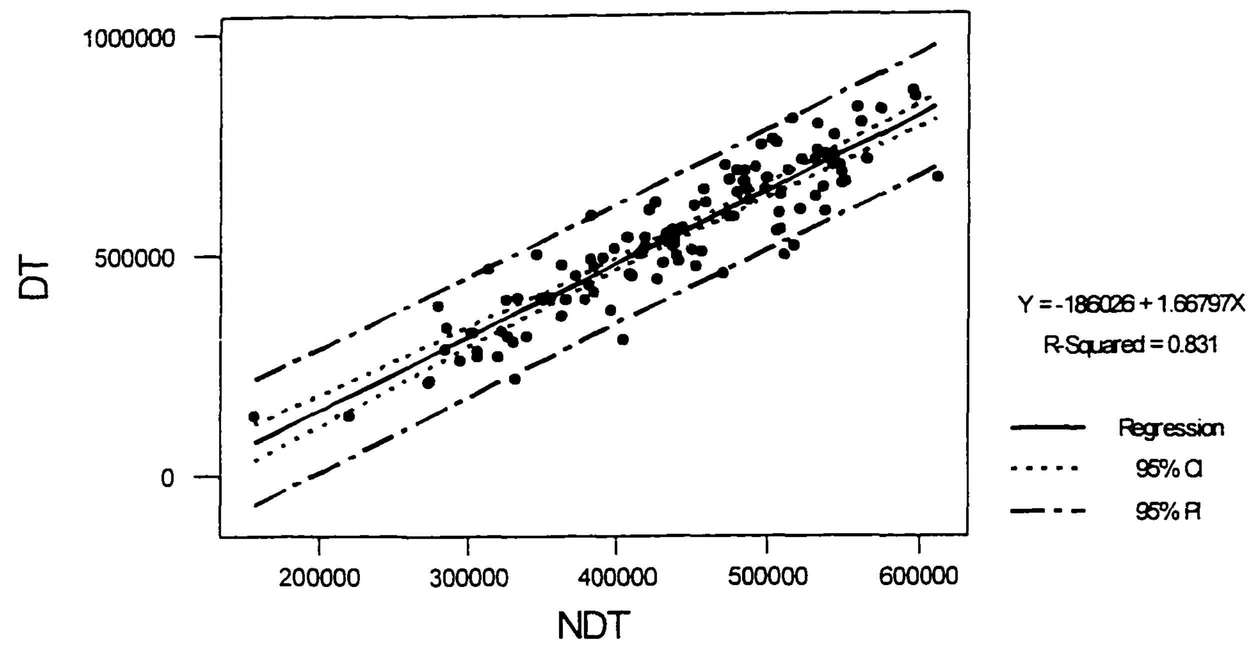

Figure 4.5. The regression line with 95% CI and 95% PI bands

Summary

The results indicated the simple linear regression model for this study is adequate in the prediction of destructive MOE values if the nondestructive MOE value is known. The results also showed that destructive test values had an influence on the linear regression equation. The within piece variance of the destructive test MOE values was close to the same value as the standard error of the correlation analysis of the destructive test MOE values versus the nondestructive test MOE values. With these values being so close to each other (≈ 5% difference), an approximation very close to the entire error in the model equation was explained from the variation within the destructive MOE values for the wood/agricultural hardboard composites used in this study. The nondestructive MOE values along with the destructive MOE values have been used to produce a linear regression model that explains 83% of the variability in the destructive test MOE values. The correlation coefficient value of .91 determined to what degree Y, the destructive test MOE value, is related to X, the nondestructive test MOE value.

The study also showed that, for the particular destructive test values obtained with the equipment used, the model associated with this study is as good as it can be due to the variance associated with the destructive tests.

CHAPTER V. CONCLUSIONS

Summary

This study was designed to determine if the modulus of elasticity (MOE) value of wood/agricultural hardboards could be found by nondestructive testing measures. Destructive measures produce waste material that could be made into useful products. A review of the literature showed this technique has been accomplished with some degree of success with wood and wood-based materials. Ultrasonic nondestructive methods were used with promising results. One of the two main research questions posed the challenge of determining if a relationship existed between the ultrasonic nondestructive test and the destructive test results for the MOE of wood/agricultural hardboards with soy-bean based adhesives. Second, if the relationship were useful could the prediction of destructive test MOE values be determined when the nondestructive test MOE value was known for the hardboards? The study showed a high correlation between the two tests, and a linear regression model was obtained through statistical analysis to ascertain the prediction of destructive test MOE values by knowing the nondestructive test MOE values.

Previous studies on nondestructive testing of wood and wood products, which were mentioned in Chapter 2, exemplify the various ways of characterizing wood and wood composites. The progression of applications of ultrasonic nondestructive testing from basic discontinuity detection to strength characterization of wood materials has provided this research with a solid foundation. These studies analyzed various sample sizes and several material uses. The materials included wood sections of bridges, plywood sheets, and hardboards. Studies also were done on the techniques of obtaining measurements from the wood products. The analysis of wood composites during its production has also yielded opportunities for the utilization of ultrasonic nondestructive testing. All of these applications have made ultrasonic nondestructive testing one of the most used methods of nondestructive testing.

This study focused on the viability of using the theory of ultrasonic nondestructive testing to characterize a new type of wood composite. The composition of the new wood-based material consisted of wood fibers, cornstalks and switchgrass with the inclusion of a soybean-based product as an adhesive for the hardboards. All previous studies of wood hardboards had used only formaldehyde as an adhesive. These two content attributes distinguished this study from previous studies from a material standpoint.

The statistical analysis of this study presented useful information on the comparison of destructive test MOE values to nondestructive test MOE values. The literature focused the destructive test as the standard to compare the nondestructive test results. Previous studies did not discuss the variability with the destructive test and materials. In the current study the variation of the destructive test was evaluated. This examination of the destructive test added certainty to the linear regression model that was developed. By calculating the variation within the destructive test and the standard error of the correlation analysis, important information was determined. The values of these two numbers played a key role in the amount of confidence in the linear regression equation that was developed. The investigation of the numbers showed the linear regression equation was as good a fit as could be for the data from this study. An understanding of this type of analysis is often overlooked, but with this type of inquiry into the data the confidence that the model produced is adequate and is well defended. This study showed prediction of destructive MOE values from nondestructive MOE values was a viable method.

Recommendations

Based on the results of this study, recommendations must be made while keeping the limitations of the study in mind.

1. Investigation into the process of making the wood/agricultural hardboards would help in the uniformity of their composition.
2. Analysis of the destructive test to determine where variation within piece could be reduced would allow for a better linear regression model.
3. Prediction of the modulus of rupture value should be investigated by using the predicted modulus of elasticity value from the nondestructive test.
4. Studies should be conducted to determine if the hardboard composition has an effect on the nondestructive test.
5. Repeatability studies should be done on how consistent a hardboard composition is made and on NDT measurements.

The use of ultrasonic nondestructive testing provides the user with the ability to detect and characterize a variety of discrete hidden discontinuities. When considering this degree of evaluation the integrity of the material is usually sacrificed. NDT provides the investigator with an alternative to destruction. Ultrasonic nondestructive is not an unflawed technique, and this method of evaluation has some disadvantages. There exist levels of imprecision and inaccuracy; therefore, standards must be adhered to when using this type of assessment for wood composites. Some methods of reducing the chance of errors include an awareness of the differences between destructive testing and nondestructive testing measurements, monitoring of the quality (i.e., statistical analysis), and agreement on the degree of permissible nonconformity.

The impact of having the ability to determine the MOE values nondestructively would impact the amount of waste material and improve the process of producing the material by monitoring construction of the materials during the process as opposed to monitoring the process upon completion.

Future Research

This study examined whether nondestructive testing methods to measure MOE for wood/agricultural hardboards could be used to predict destructive test MOE values. Future research studies could examine how the resins effect the ultrasonic signal. Other hardboards could also be considered for evaluation. The application of air-coupled transducers with this type of material would assist in the evaluation of the end product in a nonevasive manner.

The development of ultrasonic nondestructive testing to assist in the production quality of the hardboards in the Forestry Department is a viable research interest. Ideally, the NDT system would be used to evaluate the boards during the manufacturing process to correct flaws that may occur before an entire batch of material is completely processed.

This study has shown that NDT can be used to characterize this wood/agricultural material with success. As the production of this material increases, there will be a need for evaluation of the material. This study has provided the groundwork to continually improve the product with instant evaluation feedback.

APPENDIX A. FREQUENCY SPECTRUM AND FREQUENCY RANGES FOR VARIOUS APPLICATIONS OF ULTRASONIC TESTING

Electromagnetic Wave Spectrum	
Wave Type	*Frequency Range in Hertzs(Hz)*
Gamma rays	10E18 - 10E23
X-rays	10E15 - 10E20
Ultraviolet	10E14 - 10E16
Visible	10E14
Infrared	10E11 - 10E14
UTRASONIC TESTING RANGE	**25E03 - 10E08**
Short Radio Waves	10E7 - 10E12
FM. TV Bands	10E07
AM Broadcast Band	10E06
Long Radio Waves	10E00-10E05

Frequency Range	Applications
25 - 100 kHz	concrete. wood. rock. and coarse grained nonmetals
0.2 - 2.25 MHz	iron, grained metallic materials, plastics and grains
0.4 - 5 MHz	steel. aluminum. and brass
1 -2.25 MHz	welds (ferrous and nonferrous)
1 - 5 MHz	sheet plate, bars, billets
1 - 10 MHz	forgings
2.25 - 10 MHz	drawn and extruded ferrous. glass and ceramics

APPENDIX B. RAW DATA OF DESTRUCTIVE MOE VALUES AND TIME OF FLIGHT MEASUREMENTS FROM NON DESTRUCTIVE TESTS

Sample	MOE-DT	TOF (μsec)	Sample	MOE-DT	TOF (μsec)
159A1	284881	106.9	196B1	770356	87.84
159A2	403698	99.68	196B2	687368	86.88
159C1	272006	103.0	196A1	522320	98.08
159C2	469874	105.0	196A2	604017	87.20
160A1	405707	107.0	196C1	870580	85.76
160A2	477551	100.3	196C2	653584	87.52
160B1	604237	99.04	196D1	692711	89.72
160B2	517252	99.2	196D2	663247	84.96
160C1	621788	97.92	199A1	507178	88.48
160C2	559060	95.84	199A2	514916	90.24
160D1	445748	96.16	199B1	565417	89.12
160D2	505415	106.6	199B2	520468	88.80
165A1	561083	91.12	199C1	531574	89.44
165A2	365261	100.3	199C2	512382	88.96
165B1	537213	97.68	199D1	550342	89.44
165B2	401735	99.44	199D2	489566	89.92
165C1	406142	102.4	199A1	507178	88.48
165C2	493119	102.4	199A2	514916	90.24
165D1	419328	102.1	199B1	565417	89.12
165D2	374344	96.64	199B2	520468	88.80
166A1	265253	107.6	199C1	531574	89.44
166A2	305466	101.9	199C2	512382	88.96
166B1	288726	101.6	199D1	550342	89.44
166B2	221961	100.7	199D2	489566	89.92
166C1	325348	103.3	200A1	704385	84.32
166C2	337679	105.0	200A2	706700	90.40
166D1	271660	104.1	200B1	667195	89.44
166D2	315919	100.6	200B2	761612	90.24
175A1	386808	114.7	200C1	673480	91.36
175A2	324477	108.2	200C2	751252	90.88
175B1	399304	106.4	200D1	665763	89.60
175B2	481221	105.0	200D2	797953	87.84
175C1	433953	101.3	203A1	643371	87.84
175C2	503690	99.04	203A2	717711	85.68
175D1	541599	97.76	203B1	589540	85.68
175D2	500034	97.28	203B2	553160	85.20
176A1	138624	133.0	203C1	651606	86.16
176A2	139748	110.0	203C2	502728	85.20

Sample	MOE-DT	TOF (μsec)	Sample	MOE-DT	TOF (μsec)
176B1	211447	106.7	203D1	717240	85.04
176B2	218835	106.2	203D2	693169	87.04
176C1	329614	102.6	204A1	833954	87.52
176C2	317607	101.8	204A2	859271	83.92
176D1	454440	99.84	204B1	828442	85.68
176D2	310878	93.60	204B2	717826	84.88
191A1	602978	85.28	204C1	728996	85.36
191A2	484562	92.32	204C2	725189	85.68
191B1	586885	90.08	204D1	808721	86.40
191B2	702554	91.04	204D2	800040	84.16
191C1	693402	91.36	208A1	539931	90.24
191C2	652816	91.68	208A2	523424	83.76
191D1	620006	93.44	208B1	650347	86.80
191D2	677183	88.96	208B2	703874	83.92
192A1	637299	88.48	208C1	635949	84.72
192A2	614476	92.16	208C2	665550	84.40
192B1	757145	90.24	208D1	459914	86.32
192B2	624823	89.12	208D2	591680	98.00
192C1	597210	88.00			
192C2	737126	87.84			
192D1	716674	89.28			
192D2	675682	81.44			
195A1	402657	96.00			
195A2	399852	93.28			
195B1	455843	91.52			
195B2	527074	90.08			
195C1	543375	92.16			
195C2	458015	92.48			
195D1	494647	93.44			
195D2	475406	87.52			

APPENDIX C. CALCULATION OF NONDESTRUCTIVE MOE VALUES FROM TIME OF FLIGHT DATA FOR WOOD/AGRICULTURAL HARDBOARDS

Sample	TOF (μsec)	length (in)	width (in)	thick (in)	wgt. lbs	grav. accel m/sec-sec	MOE-NDT
159A1	106.90	9.00	2.02	0.13	0.040	384	312407
159A2	99.68	9.00	2.03	0.13	0.039	384	348594
159C1	103.00	9.00	2.02	0.13	0.038	384	319688
159C2	105.00	9.00	2.03	0.13	0.038	384	306110
195A1	96.00	9.00	2.02	0.13	0.035	384	338955
195A2	93.28	9.00	2.01	0.12	0.035	384	384456
195B1	91.52	9.00	2.03	0.13	0.038	384	402924
195B2	90.08	9.00	2.02	0.12	0.038	384	445376
195C1	92.16	9.00	2.03	0.12	0.037	384	412261
195C2	92.48	9.00	2.03	0.12	0.037	384	409413
195D1	93.44	9.00	2.03	0.12	0.037	384	401043
195D2	87.52	9.00	2.01	0.12	0.037	384	461682
199A1	88.48	9.00	2.01	0.13	0.039	384	446834
199A2	90.24	9.00	2.00	0.13	0.039	384	431722
199B1	89.12	9.00	2.03	0.13	0.040	384	447282
199B2	88.80	9.00	2.02	0.14	0.040	384	420403
199C1	89.44	9.00	2.03	0.14	0.040	384	412367
199C2	88.96	9.00	2.02	0.13	0.040	384	451115
199D1	89.44	9.00	2.03	0.14	0.042	384	432985
199D2	89.92	9.00	2.03	0.14	0.042	384	428375
166A1	107.60	9.00	2.03	0.13	0.038	384	291495
166A2	101.90	9.00	2.03	0.13	0.038	384	325018
166B1	101.60	9.00	2.02	0.15	0.038	384	284751
166B2	100.70	9.00	2.03	0.13	0.038	384	332810
166C1	103.30	9.00	2.03	0.13	0.037	384	307945
166C2	105.00	9.00	2.03	0.14	0.037	384	276764
166D1	104.10	9.00	2.02	0.13	0.037	384	304731
166D2	100.60	9.00	2.02	0.13	0.037	384	326304
176A1	133.00	9.00	2.03	0.13	0.031	384	155643
176A2	110.00	9.00	2.02	0.14	0.031	384	212328
176B1	106.70	9.00	2.03	0.14	0.037	384	268016
176B2	106.20	9.00	2.02	0.14	0.037	384	271885
176C1	102.60	9.00	2.03	0.14	0.040	384	313366
176C2	101.80	9.00	2.02	0.13	0.040	384	344493
176D1	99.84	9.00	2.02	0.13	0.042	384	376060

Sample	TOF (μsec)	length (in)	width (in)	thick (in)	wgt. lbs	grav. accel m/sec-sec	MOE-NDT
176D2	93.60	9.00	2.02	0.14	0.042	384	397310
203A1	87.84	9.00	2.03	0.14	0.043	384	459590
203A2	85.68	9.00	2.03	0.13	0.043	384	520213
203B1	85.68	9.00	2.00	0.14	0.040	384	456094
203B2	85.20	9.00	2.02	0.13	0.040	384	491810
203C1	86.16	9.00	2.02	0.13	0.040	384	480912
203C2	85.20	9.00	2.01	0.13	0.040	384	494257
203D1	85.04	9.00	2.01	0.13	0.041	384	508521
203D2	87.04	9.00	2.02	0.13	0.041	384	483017
208A1	90.24	9.00	2.03	0.13	0.039	384	425342
208A2	83.76	9.00	2.02	0.12	0.039	384	528678
208B1	86.80	9.00	2.03	0.12	0.040	384	502430
208B2	83.92	9.00	2.02	0.12	0.040	384	540168
208C1	84.72	9.00	2.04	0.12	0.040	384	524819
208C2	84.40	9.00	2.03	0.12	0.040	384	531411
208D1	86.32	9.00	2.04	0.13	0.040	384	474433
208D2	98.00	9.00	2.03	0.13	0.040	384	369896
160A1	107.00	9.00	2.01	0.13	0.042	384	329044
160A2	100.30	9.00	2.04	0.13	0.042	384	368965
160B1	99.04	9.00	2.04	0.13	0.045	384	405442
160B2	99.20	9.00	2.03	0.13	0.043	384	388076
160C1	97.92	9.00	2.04	0.13	0.045	384	414770
160C2	95.84	9.00	2.04	0.13	0.044	384	423347
160D1	96.16	9.00	2.03	0.13	0.043	384	413001
160D2	106.60	9.00	2.01	0.13	0.042	384	331518
165A1	91.12	9.00	2.03	0.13	0.047	384	502739
165A2	100.30	9.00	2.04	0.13	0.042	384	368965
165B1	97.68	9.00	2.03	0.13	0.045	384	418864
165B2	99.44	9.00	2.03	0.13	0.041	384	368242
165C1	102.40	9.00	2.03	0.13	0.040	384	338791
165C2	102.40	9.00	2.02	0.13	0.044	384	374515
165D1	102.10	9.00	2.02	0.13	0.044	384	376719
165D2	96.64	9.00	2.03	0.13	0.041	384	389890
175A1	114.70	9.00	2.03	0.12	0.038	384	273346
175A2	108.20	9.00	2.00	0.13	0.039	384	300295
175B1	106.40	9.00	2.03	0.13	0.040	384	313797
175B2	105.00	9.00	2.01	0.13	0.045	384	366105
175C1	101.30	9.00	2.03	0.13	0.044	384	380808

Sample	TOF (μsec)	length (in)	width (in)	thick (in)	wgt. lbs	grav. accel m/sec-sec	MOE-NDT
175C2	99.04	9.00	2.02	0.13	0.046	384	418556
175D1	97.76	9.00	2.03	0.13	0.045	384	418179
175D2	97.28	9.00	2.01	0.13	0.046	384	435996
191A1	85.28	9.00	2.02	0.13	0.042	384	515432
191A2	92.32	9.00	2.04	0.14	0.044	384	423657
191B1	90.08	9.00	2.02	0.13	0.043	384	472964
191B2	91.04	9.00	2.03	0.12	0.043	384	490975
191C1	91.36	9.00	2.03	0.12	0.042	384	476203
191C2	91.68	9.00	2.03	0.13	0.042	384	443784
191D1	93.44	9.00	2.02	0.12	0.042	384	457492
191D2	88.96	9.00	2.03	0.12	0.042	384	502244
192A1	88.48	9.00	2.04	0.12	0.042	384	505220
192A2	92.16	9.00	2.04	0.12	0.041	384	454590
192B1	90.24	9.00	2.03	0.12	0.043	384	499719
192B2	89.12	9.00	2.05	0.13	0.042	384	465064
192C1	88.00	9.00	2.04	0.13	0.043	384	490728
192C2	87.84	9.00	2.03	0.12	0.044	384	539664
192D1	89.28	9.00	2.02	0.12	0.045	384	536913
192D2	81.44	9.00	2.03	0.13	0.044	384	589181
196A1	98.08	9.00	2.03	0.12	0.042	384	413184
196A2	87.20	9.00	2.01	0.13	0.043	384	507233
196B1	87.84	9.00	2.03	0.12	0.044	384	539664
196B2	86.88	9.00	2.01	0.13	0.045	384	534743
196C1	85.76	9.00	2.03	0.12	0.045	384	579026
196C2	87.52	9.00	2.02	0.13	0.045	384	524342
196D1	89.72	9.00	2.02	0.12	0.043	384	508031
196D2	84.96	9.00	2.03	0.12	0.043	384	563761
200A1	84.32	9.00	2.03	0.12	0.042	384	559041
200A2	90.40	9.00	2.04	0.13	0.042	384	454203
200B1	89.44	9.00	2.03	0.13	0.043	384	477394
200B2	90.24	9.00	2.03	0.13	0.045	384	490779
200C1	91.36	9.00	2.02	0.13	0.045	384	481190
200C2	90.88	9.00	2.01	0.13	0.045	384	488706
200D1	89.60	9.00	2.01	0.13	0.043	384	480424
200D2	87.84	9.00	2.02	0.13	0.045	384	520528
204A1	87.52	9.00	2.01	0.13	0.047	384	550370
204A2	83.92	9.00	2.01	0.12	0.045	384	610713

Sample	TOF (µsec)	length (in)	width (in)	thick (in)	wgt. lbs	grav. accel m/sec-sec	MOE-NDT
204B1	85.68	9.00	2.01	0.13	0.047	384	574263
204B2	84.88	9.00	2.00	0.13	0.044	384	550529
204C1	85.36	9.00	2.02	0.13	0.042	384	514466
204C2	85.68	9.00	2.01	0.13	0.043	384	525390
204D1	86.40	9.00	2.01	0.12	0.040	384	512139
204D2	84.16	9.00	2.02	0.12	0.042	384	563947

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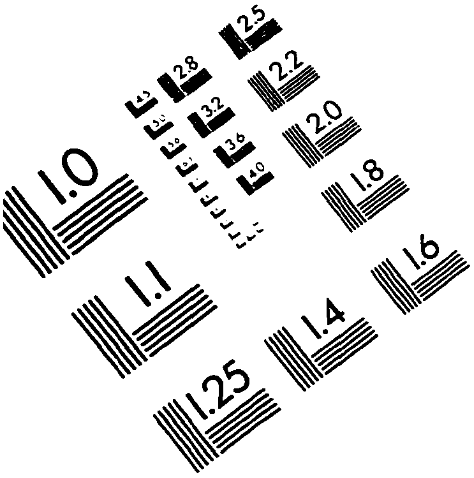
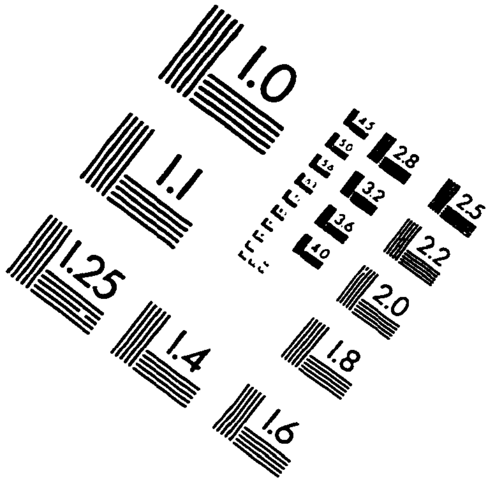
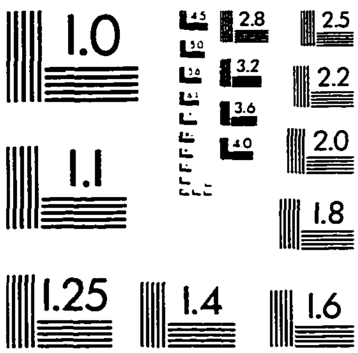
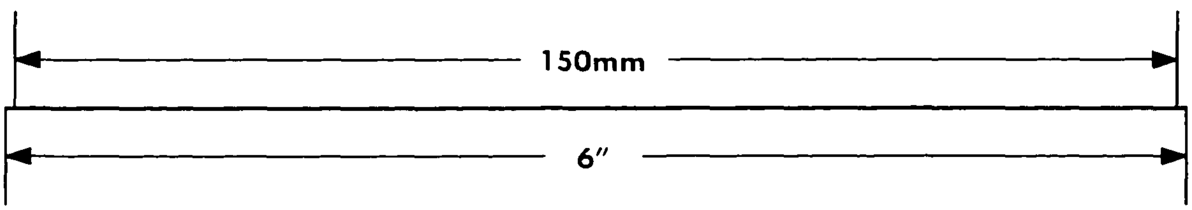
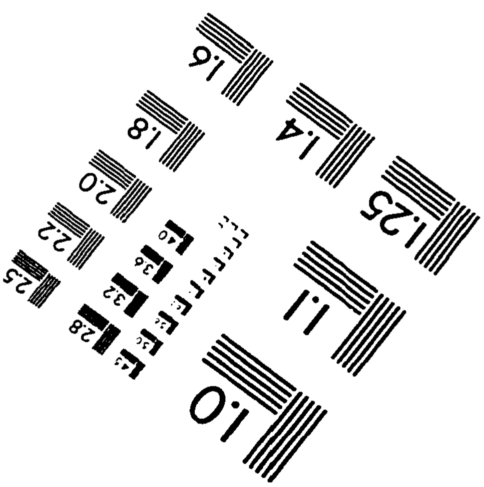
IMAGE EVALUATION TEST TARGET (QA-3)











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