ESTIMATING LUMBER PROPERTIES WITH ACOUSTIC-BASED TECHNOLOGIES—PART 2: ULTIMATE TENSION STRESS ESTIMATION FROM TIME- AND FREQUENCY-DOMAIN PARAMETERS[1]

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Abstract. This research article summarizes results from Part 1 of a study designed to examine the use of advanced signal processing techniques with acoustic-based lumber assessment technologies to evaluate the MOE and ultimate tension stress (UTS) of structural lumber. In Part 1 of this research, a mathematical model of acoustic wave behavior in an idealized specimen is derived using fundamental mechanics. In Part 2, wave behavior is examined experimentally in a series of 38 38 2438-mm wood specimens. The specimens vary considerably in visual character. Several of the specimens are, from a visual assessment, clear of naturally occurring defects such as knots. Conversely, strength-reducing defects such as knots are visible in several specimens. The presence of naturally occurring defects can affect acoustic waves in a variety of ways. A few examples include altering wave speed, changing the wave travel path, and/or converting the wave from longitudinal waves to shear waves or back through mode conversion. These alterations can cause wave behavior to deviate from the behavior observed in clear wood specimens. Deviations are observable in both time and frequency domains. From the differences, parameters are identified which improve estimation of UTS.

Keywords: Frequency, clear wood, lumber, ultimate tension stress.

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INTRODUCTION

Wood is a biological material with inherent variation and internal features, which may not always be visible on the exterior. The collection of the sample has the goal of creating a continuum of tension strength values from low to high among the specimens. A particularly dense piece of wood, with a high number of rings per centimeter, which contains a knot may have higher tension strength than a defect-free piece, that is, low density with a low number of rings per centimeter. The presence or absence of defects does not necessarily give an insight into the ultimate tension strength of an individual piece. In Part 1, a model is developed to aid in identifying relevant characteristics. In Part 2, the ultimate tension stress (UTS) is estimated from characteristics of the time and frequency domains. The goal of the entire study was to accurately assess the tensile strength of the wood.

Various nondestructive methods are currently used to evaluate, sort, and grade structural lumber. Evaluation of visual characteristics of a piece of lumber is arguably the most widely used nondestructive evaluation technique in the forest products industry. Characteristics such as the size, number, and location of knots are common visual characteristics considered when grading lumber. Research has shown that several physical and mechanical characteristics can be used to assist in the grading of lumber such as density, acoustic wave speed, MOE, and transverse vibration. Out of this research has evolved commercially available, rugged equipment that is used in the lumber grading process (Ross 2015).

One of the technologies that are currently in use is based on measurement of the acoustic properties of a lumber specimen. Specifically, the speed at which mechanically induced acoustic waves flow along the length of a specimen is measured and coupled with its density to determine its MOE. The MOE, in turn, is used to estimate the MOR in bending and UTS parallel to grain. Unfortunately, the MOE currently accounts for only 50-55% of the variation in the MOR or UTS, and additional factors are needed for estimation of lumber strength. This information, along with certain visual inputs, can result in the assignment of a grade to the piece of lumber.

The flow of an acoustic wave in a lumber specimen is influenced by a variety of factors, such as the size, number, and location of knots; slope of grain; presence decay; and many others. It is widely accepted that these factors have an influence on the MOE, MOR, and UTS of lumber. The working hypothesis of this study is that many of these factors impact the MOE, MOR, and UTS and affect wave behavior; therefore, waves traveling through the wood may contain information about the factors that can be used to better estimate the MOE, MOR, and UTS. In this study, the focus is on better estimation of UTS.

The acoustic measurement system currently used to determine the MOE of structural lumber yields an electronic signature that contains additional information regarding the movement of an acoustic wave in the lumber. Although a significant number of published research findings exist on the measurement and use of acoustic-based MOE for evaluating lumber and other wood products, little more than cursory information is published on the effects that naturally occurring wood characteristics have on acoustic wave behavior in lumber and the potential impact they have on evaluating lumber strength.

The objectives of the research presented here were to 1) examine fundamental acoustic wave behavior in clear wood and lumber, 2) explore the effect that naturally occurring defects such as knots have on acoustic wave behavior in lumber, and 3) investigate the possibility of using advanced signal processing techniques to enhance acoustic-based lumber property estimation.

The research herein begins with an examination of the theoretical foundation of acoustic wave behavior in an idealized homogeneous viscoelastic bar of similar thickness and length to that of a lumber specimen. A review of published research on acoustic wave behavior in clear wood and lumber specimens is conducted, including published works that examined the effects that naturally occurring characteristics (such as knots) have on wave behavior. Laboratory tests are then conducted on a sample of lumber specimens, and advanced signal processing techniques are used to analyze acoustic wave signatures obtained.

Longitudinal Wave Behavior in Wood

Foundation studies with clear wood and lumber specimens. Several studies have been conducted to examine wave behavior in wood. Bertholf (1965) conducted an evaluation of the basic wave theory and its applicability to small, clear wood specimens. He predicted acoustic wave behavior with strain measurements and verified the dependence of wave propagation velocity on the MOE of clear wood. Galligan and Bertholf (1963) used 1.9 1.9 76.2-cm clear wood specimens in a study designed to examine the use of piezoelectric properties to examine wave behavior. They compared measurements of dynamic strain patterns made using strain gauges and piezoelectric probes and observed comparable results. They also examined the relationship between dynamically measured MOE vs MOE obtained from compression tests parallel to the fiber axis. A strong linear relationship was observed through graphical representation of the data, but no coefficient of determination (r^2) value was given.

Galligan and Courteau (1965) and Pellerin and Galligan (1973) found that the MOE, as determined by measuring the propagation velocity of induced acoustic waves, could be used to predict the static bending MOE of lumber specimens. They used 40 pieces of Douglas fir structural lumber in their experiment and obtained an excellent correlation between modulus values, with an r^2 value of 0.914.

Effect of natural characteristics on wave behavior. Knots and the area surrounding them in lumber have several characteristics that impact wave behavior and lumber strength. First, a knot is the tissue from a branch or limb of a tree. Its fibers are aligned parallel to its axis; hence, its fibers do not align with the longitudinal axis of a piece of lumber. Rather, knots in lumber are an anomalous interruption to otherwise straight grain. Second, the fibers surrounding a knot in a piece of lumber are formed in the tree in a manner so as they flow around the branch or limb. Consequently, they also do not align with the longitudinal axis of a piece of lumber. Third, the cell wall structure of the fibers surrounding a knot is significantly different from that of the fibers in clear wood areas of a piece of lumber (Ross 2010). Knots can be significant strength-reducing (and thereby economic value–reducing) characteristics for structural lumber. The effect that the location and size of knots have on strength is well documented. ASTM D 4761-19 (2019b) contains a formalized system of cataloging knot shapes, sizes, and locations of knots. ASTM D 245-07 (2019a) contains strength ratio formulas that relate the estimated strength of a piece of wood based on the location and size of the knot to a piece that is clear of defects. Both standards are used in determining design values for structural lumber.

The fundamental wave theory concludes that an interface in the path of flow of a wave will cause all or a portion of a wave energy to reflect from it. A wave traveling in a medium will respond to differences in properties of the medium. For example, a longitudinal wave traveling in a piece of lumber will increase or decrease in velocity because of increases or decreases in the MOE (Graff 1975).

Several researchers have investigated the effects of anomalous zones on wave propagation in wood. Ross (1984) conducted an experiment designed to explore the effect an interface, such as the distinct boundary observed with knots in lumber, has on longitudinal wave behavior in wood. He used a 38 89-mm 3.66-m clear Douglas fir wood specimen. For this clear wood specimen, the observed wave behavior was as predicted by the fundamental theory and mechanics. It showed a series of equally spaced pulses, with no intermediate pulses. Also, the pulses decreased in magnitude with time, as expected. To explore the effect an interface would have on wave behavior, he introduced a 3   25.4-mm deep saw kerf in the specimen. The observed wave behavior was analyzed by studying experimental results and comparing them with position vs time plots of the wave. He concluded that the saw kerf introduced an interface, resulting in reflection of part of the wave energy. Divos and Sugiyama (1996) confirmed these results in an experiment they conducted using clear wood spruce and wood composite specimens. They demonstrated that using this information, they could predict the size and location of defects.

Jung (1979) designed and conducted an experiment to investigate the use of acoustic wave grading techniques for wood veneers. It was revealed that wave propagation velocities decreased in the presence of knots, with higher velocities found in defect-free areas of veneer sheets. To explore this phenomenon in lumber, Ross (1985) prepared specimens composed from several of wood-based materials of known static mechanical properties. Materials tested included solid sawn lumber with knots, solid sawn lumber without defects, and wood-based particle composites. The specimens were impacted at one end using a pendulum impactor. Acoustic wave propagation times were measured through sections of the overall specimen. Wave speed was shown to be a function of the MOE even in specimens which had internally varying MOE.

MATERIALS AND METHODS

The specimens used in the experimental phase of this study are cut from a sample of visually graded (No. 2) southern pine 38   184-mm dimension lumber (nominal 2   8 in). From the lumber, 103 38   38-mm   2.44-m specimens are cut as shown in Fig 1. These specimens are conditioned to approximately 12% EMC before testing in a room kept at constant conditions of 21°C and 65% relativity humidity. The dimensions and weight of each specimen are measured before testing.

The experimental setup for conducting acoustic wave testing on lumber is illustrated in Fig 2. To insulate the specimen from external vibrations, supports made of ethylene–vinyl acetate foam rubber are used. A pendulum with a 5-g lead mass is used as the excitement system. The pendulum is raised to a height of 15 cm during all tests to ensure the same impact energy for all specimens. The longitudinal acoustic waves that traveled through the piece are recorded. The primary sensing element is a small, commercially available microphone and condenser (microphone USB 2.0 and condenser SF-555B, with a frequency response range of 100 Hz-16 KHz and a sensitivity of   47   4 dB). This device is coupled to an IBM compatible laptop personal computer (Dell Model Latitude E6540, Round Rock, TX). Software from the Fakopp Portable Lumber Grader (version 2.0) is used for data acquisition and waveform analysis (Fakopp 2005).

The time-domain signal from each specimen is recorded, and Fourier transformation is performed to

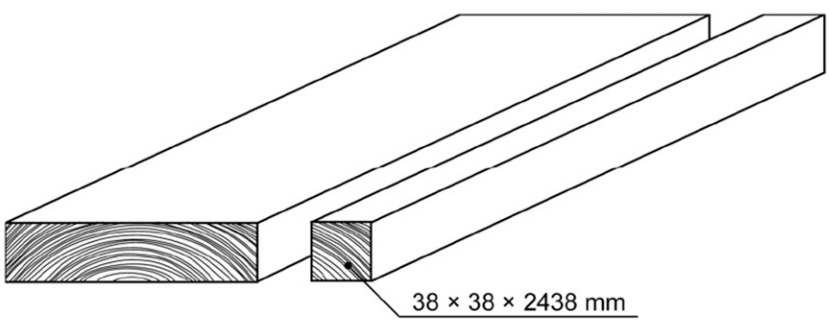

Figure 1. Construction of specimens.

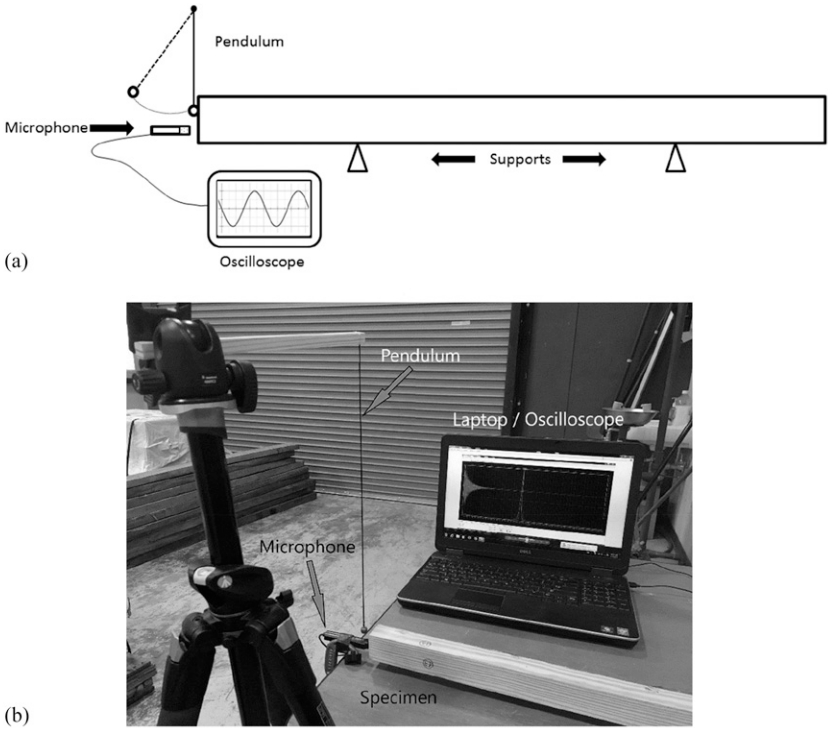

Figure 2. Test setup for recording acoustic waves: (a) diagram and (b) experimental setup.

observe the frequency domain spectrum. The fundamental frequency of each of the 103 specimens is determined from the frequency domain of each recorded signal. The MOE of each piece is then calculated from the fundamental frequency peak.

A common method of estimating UTS of lumber is to develop linear relationships between UTS and dynamic MOE (MOE_D). Using MOE_D as an independent variable yields an estimate of the dependent UTS that normally accounts for 50-55% of the variance in the UTS values. In this study, the fundamental frequency of 103 pieces of 38 38-mm 2.44-m lumber was measured. The mass is also measured. The MOE_D is then estimated using the formula in Eq 1 which is derived from longitudinal wave motion through an elastic solid (Graff 1975):

$$MOE_D = \left(\frac{m}{v}\right)(2Lf_r)^2, \quad (1)$$

where MOE_D is the dynamic MOE in Pa, m is the mass of the specimen in kg, v is the volume of the specimen in cubic meters, L is the length of the specimen in meters, and f_r is the longitudinal fundamental frequency of the specimen in Hz.

After the acoustic signals are recorded for all specimens, the sample is tested destructively in tension. Testing is performed on a Metriguard 412 Tension Proof Loader at Mississippi State University. The proof loader held each end of the specimen using metal grips and over time pulls the sample in tension until failure. If failure occurred within the grips, the specimen is omitted from the data set. The span of testing in the Metriguard is 0.978 m. During testing, both tension load and displacement are measured. The tension load is used to calculate tension stress. Displacement is converted to strain. Linear regression is used to find the slope for the line relating tension stress to tension strain; the slope of the line is the tension MOE (MOE_T). The UTS for each specimen is the maximum tension stress.

Figure 3(a) shows a typical acoustic wave signal collected from a specimen (specifically, specimen

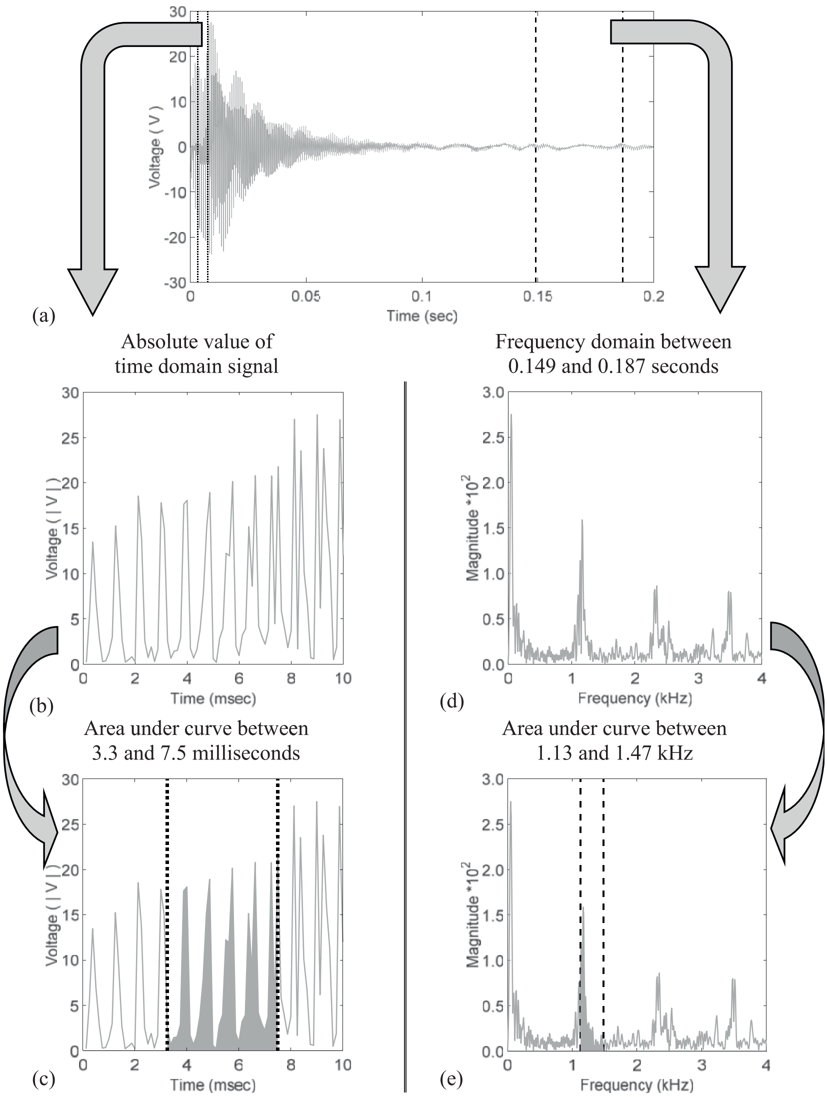

Figure 3. Development of parameters for multivariable linear regression. Left: area under the curve for the time-domain signal between 3.3 and 7.5 ms. This process is described in Fig 4. Right: area under the curve between 1.13 and 1.47 kHz of the frequency domain of a window between 0.149 and 0.187 s. This process is described in Fig 5.

No. 40). The sampling frequency is 8000 Hz; the time step between samples is 0.000125 s. Two regions are the focus of preliminary assessment: the earliest arrival of the signal and late in the signal when the wave energy begins to attenuate. A clear piece of wood should have little disruption to the wave as it travels from one end of the specimen to the other. In a specimen with features such as knots and slope of grain, the signal will be disrupted through reflection, mode conversion, and increased attenuation. The change should be observable. Figure 3(b) shows an early time portion of a collected signal. The absolute value of the time-domain signal is shown in Fig 3(c). The area under the curve within the time window between 0.0033 and 0.0075 s is selected as the parameter to improve the UTS estimate. The correlation between the area under the curve within the specified region and UTS was higher than any other portion of the time-domain signal and is within the range of time expected to be most noticeably affected by the presence of defects. This determination was through a "brute force" calculation method that searched for correlation between UTS and the area under the curve for time windows ranging from 0.00125 (10 time steps) to 0.125 (1000 time steps) second in increments of 0.000125 (one time step) second. Every portion of the time-domain signals is examined for all window sizes. The process is described in Fig 4.

McGovern et al. (2013) stated that higher frequencies within wood have higher attenuation than lower frequencies. Mode conversion in the area of knots causes wave energy to shift into higher frequencies and undergo higher attenuation. Clear wood provides fewer opportunities for mode conversion, and therefore, less wave energy

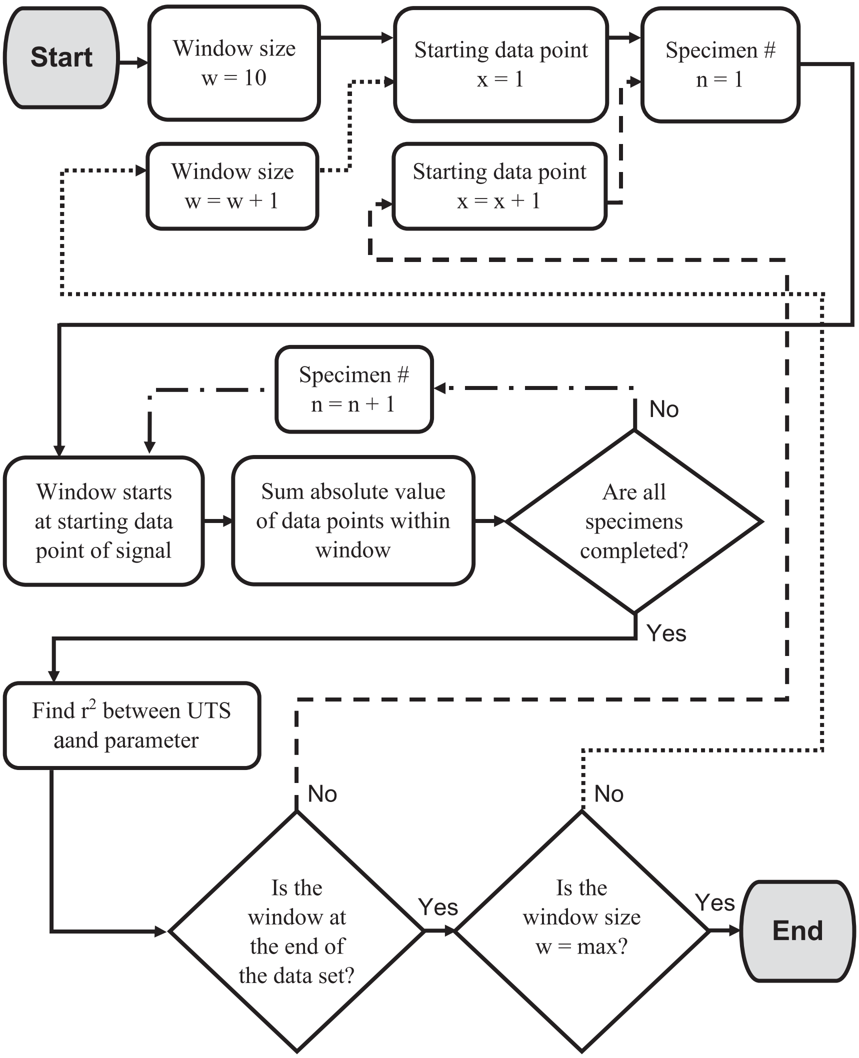

Figure 4. Flowchart describing the process of identifying the width and center of a window within the data set that most closely correlates with ultimate tension stress (UTS). For Fig 3(c), the maximum window size used is 1000 data points; for Fig 3(e), the maximum is half of the window size of Fig 5.

is lost to attenuation. The most powerful and persistent frequencies measured should be the fundamental frequency and subsequent harmonics. The magnitude of the frequencies above the fundamental frequency should be higher in clear wood than in specimens with defects. In Fig 3(d), the frequency domain of the time-domain signal between 0.149 and 0.187 s is shown. Within that frequency domain, the area under the curve for the frequency range of 1.13-1.47 kHz is chosen as the parameter to estimate UTS, as shown in Fig 3(e). The correlation between the area under the curve within the specified region and UTS is higher than any other portion of the frequency-domain signal. This determination was made using the "brute force" method described earlier and in Fig 4, with an additional step. A process of choosing a window from the time-domain signal to convert to frequency-domain takes place before examining the area under the frequency-domain curve. A range of window sizes between 256 data points and 2048 data

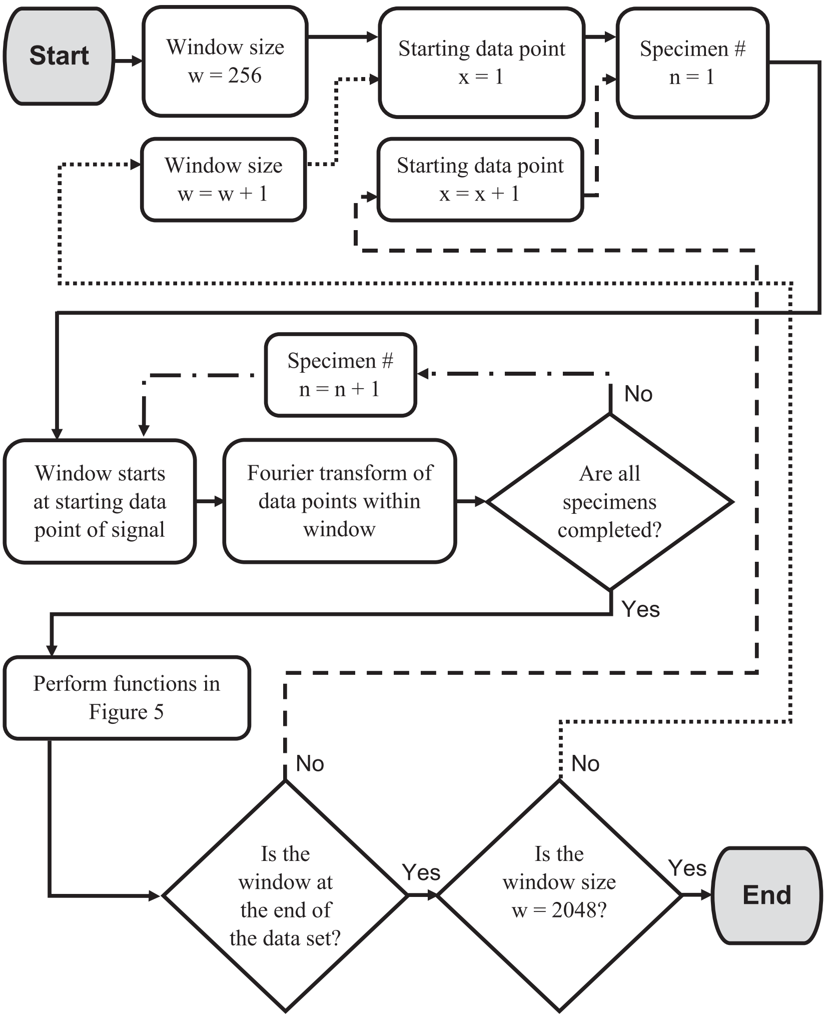

Figure 5. Flowchart describing the process of identifying the width and center of a window within the data set on which Fourier transform is performed. The resulting frequency domain is then subjected to the process given in Fig 4 to find a parameter that most closely correlates.

points are selected from the time domain and converted to the frequency domain. Every portion of the time-domain signals is converted to the frequency domain for all window sizes. The process is described in Fig 5.

RESULTS AND DISCUSSION

A first-order relationship between the MOE_D and UTS is developed using linear regression and is shown in Fig 6. The coefficient of determination (r^2) for the linear regression line is 0.52, indicating that 52% of the variation of the dependent variable, UTS, is explained by the model. The root mean square (RMS) error of the model is 20.48 MPa. Using MOE_D to estimate UTS relies on two parameters: density and fundamental frequency. By examining the time and frequency domains of the mechanical wave signals collected from the specimens during testing, two additional parameters are identified to improve the estimation.

A multivariable linear regression (MLR) is performed using the variables weight (w), fundamental frequency (f_r), the area under the time-domain curve identified in Fig 3(c) (A_t), the area under the frequency-domain curve identified in Fig 3(e) (A_m), and a constant (k). Mathworks MATLAB R2019a "regress" function is used to perform the regression. The new model is shown in Fig 7. The r^2 value increases from 0.52 using only MOE_D to estimate UTS in Fig 6 to a value of 0.71 in Fig 7 using MLR. The RMS error of the new model decreases from 20.48 to 16.47 MPa. The formula for the improved model is given in Eq 2. The coefficients for each of the parameters are given in Table 1.

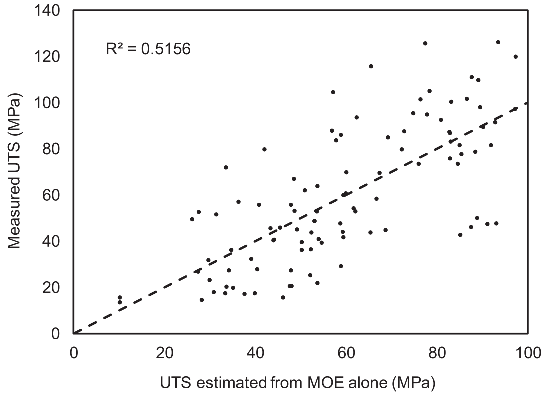

Figure 6. Estimate of ultimate tension stress (UTS) values from dynamic MOE. The root mean square error of this method is 20.48 MPa for the set.

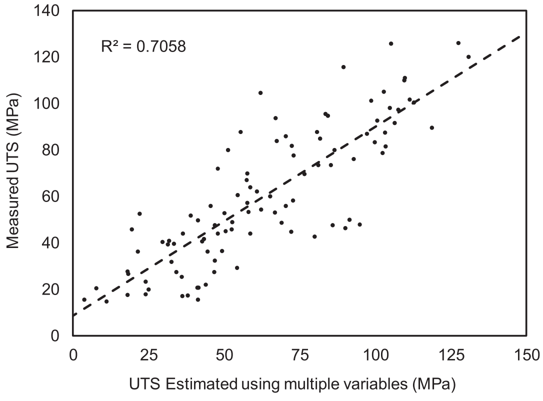

Figure 7. Estimate of ultimate tension stress (UTS) using multivariable linear regression given in Eq 2. The r^2 value is 0.7058, and the root mean square error is 16.47 MPa.

$$UTS = a_1k + a_2\rho + a_3f_r + a_4A_t + a_5A_m, \quad (2)$$

where UTS is the ultimate tension stress, $a_{1\text{-}5}$ are coefficients of the MLR, k is a constant, ρ is the density of the specimen, f_r is the longitudinal fundamental frequency of the specimen, A_t is the area under the time-domain curve between 0.0033 and 0.0075 s, and A_m is the area under the frequency-domain curve between 1128 and 1486 Hz.

CONCLUSIONS

The UTS is estimated using a widely accepted method of linear regression using MOE_D as the independent variable. This method yields a coefficient of determination of 0.52. Additional parameters related to early arrival energy of the time-domain signal and late time loss of energy around the fundamental frequency are identified as variables that improve the estimation of UTS. A new MLR model is constructed. The improved model yields a coefficient of determination of 0.71, an improvement of 37% over MOE_D estimations alone. Also, the RMS error of the MOE_D

Table 1. Multivariable linear regression coefficients.

Parameter	Symbol	MLR coefficient	p value
Constant	k	111.7	$2.51\ \ 10^{7}$
Weight	P	234.0	$5.90\ \ 10^{11}$
Fundamental frequency	f_r	0.1012	$3.67\ \ 10^{4}$
Frequency-domain area	A_m	0.1913	$3.50\ \ 10^{5}$
Time-domain area	A_t	0.0691	$2.18\ \ 10^{6}$

estimation of UTS is 20.48 MPa, whereas the RMS error of the multiparameter model is 16.47 MPa, which is a decrease in error of 20%. Future work in this area includes examining the position of peaks other than the fundamental frequency and its harmonics to determine if they provide additional information about the location and severity of defects within the specimens.

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