United States Department of Agriculture

Foundation of Nondestructive Testing of Wood Products

Contributions from an Industrial Research Engineer

Friend K. Bechtel
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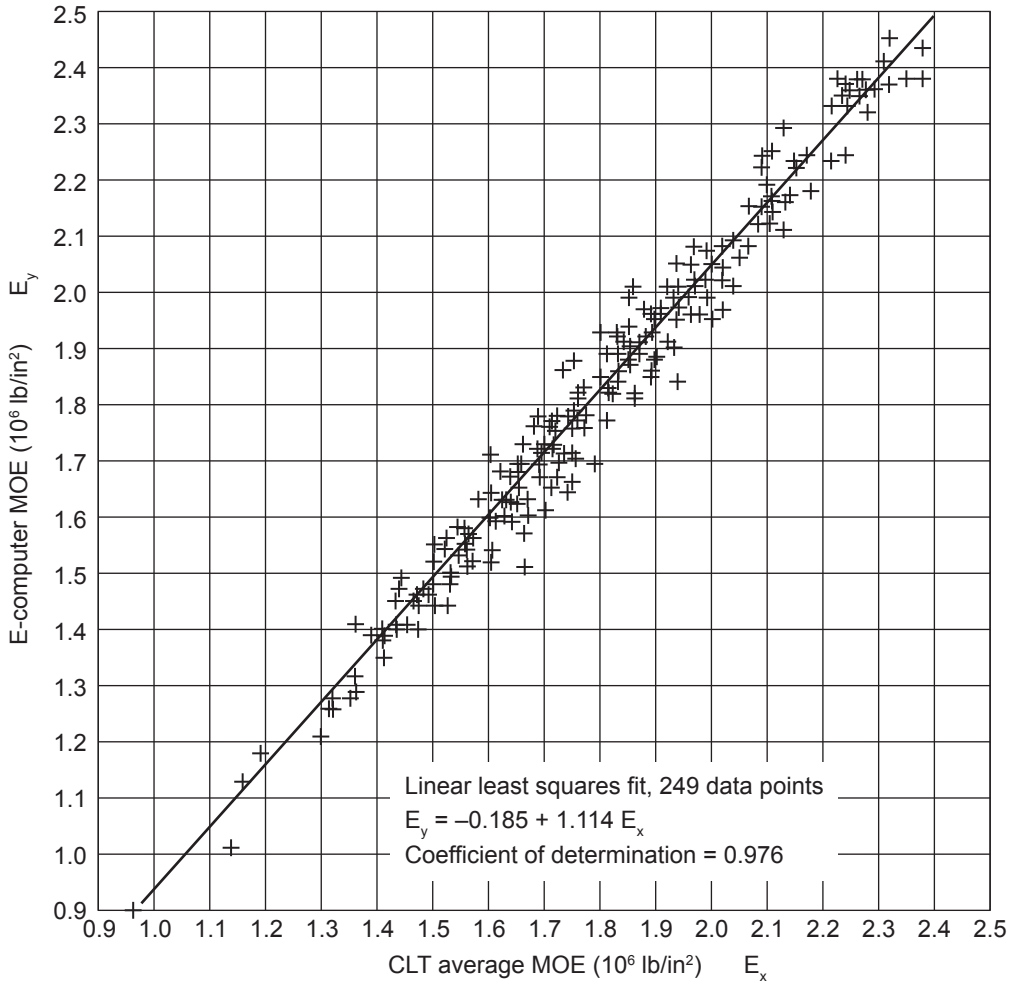

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Abstract

Nondestructive evaluation procedures are now widely used in the forest products industry. These procedures rely upon nondestructive tests to evaluate important physical and mechanical properties of wood-based materials and began with fundamental research during and after World War II. An important outcome was the evolution of machinery and process for grading lumber and veneer. A dedicated group of scientists and engineers conducted and adapted this research for industrial use and developed equipment to make accurate measurements of wood properties in a production setting. One of those engineers, Dr. Friend K. Bechtel, spent over 40 years developing modern testing equipment for use by the forest products industry. Among his significant contributions to the nondestructive testing field is his fundamental analytical work. Most of his design work began with a thorough evaluation of a test method, starting with underlying physical and mechanical principles. As an industrial research engineer, he focused on designing quality equipment that would provide accurate information to manufacturers and users of wood products. This publication describes some of his work in context with that of others, some previously reviewed and published and some not. It begins with a history of the industrial development of the machine stress rating lumber grading process. It then summarizes analytical work that delves into the effects that nonhomogeneities frequently found in wood products have on their mechanical properties.

Keywords: Nondestructive evaluation, wood, forest products

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Preface

Wood is an interesting and useful material, and products made from wood have been used since ancient times. Prehistoric users of wood likely performed some sort of testing to ensure that it would meet requirements for tools and structures. One of the early uses of a nonvisual nondestructive testing method involved a procedure to evaluate timbers for boats used by the Hudson Bay Company, Canada:

> A York boat, which took two skilled men two weeks to build, would last three seasons with minimum maintenance. The trickiest part of the construction process was to find the proper piece of spruce or tamarack for a seaworthy keel. Samples were tested by being placed on stocks and a pocket watch held against the butt at one end. The builder listened for the tick at the other. Only if the ticking resonated loudly and clearly through the wood was it judged suitable to withstand the stresses of being carved into a keel. (From *Caesars of the Wilderness: Company of Adventures, Volume II*, by Peter C. Newman.)

Nondestructive evaluation procedures are now widely used in the forest products industry, from grading logs to evaluating historic wood artifacts and structures. These procedures rely upon nondestructive tests to evaluate important physical and mechanical properties of wood-based materials and began with fundamental research during and after World War II. The purpose was to more efficiently use the wood resource. Universities, government laboratories, and industrial research centers developed testing techniques and methodologies to assign appropriate design values for wood products. An important outcome was the evolution of machinery and process for grading lumber and veneer.

A dedicated group of scientists and engineers conducted and adapted this research for industrial use and developed equipment to make accurate measurements of wood properties in a production setting—a demanding environment—on a daily basis.

One of those engineers, Dr. Friend K. Bechtel, an electrical engineer by training, spent over 40 years developing modern testing equipment for use by the forest products industry. He worked on the development and design of equipment to grade lumber, evaluate veneer, and test structural timbers. This was first as Director of Research and Vice President of Metriguard Inc., in Pullman Washington, USA, and then on his own with Kierstat Systems LLC, in Mead, Washington, USA.

Among his significant contributions to the nondestructive testing field is his fundamental analytical work. He took a scientifically rigorous approach in his assessment of a test method and in his equipment designs. Most of his design work began with a thorough evaluation of a test method, starting with underlying physical and mechanical principles. As an industrial research engineer, he focused on designing quality equipment that would provide accurate information to manufacturers and users of wood products.

This publication describes some of his work in context with that of others, some previously reviewed and published and some not. It begins with a history of the industrial development of the machine stress rating lumber grading process. It then summarizes analytical work that delves into the effects that nonhomogeneities frequently found in wood products have on their mechanical properties.

Easy access to previous work is important in any research effort. This publication summarizes Bechtel's work in context with that of others, and its purpose is to capture and compile some of this work and provide references for use by current and future scientists and engineers working on nondestructive testing of wood products. For his own use, Bechtel sometimes wrote about other subjects that were important to this work, and some of that is included for the possible benefit of others. Much work remains to be done, and suggestions for some future research directions are included.

The forest products business is interesting, challenging, and fulfilling. Bechtel has expressed his thanks to all the many friends and acquaintances he has had the pleasure of meeting and working with over the years. Memory and space do not allow mention of all their names and helpful inputs.

Robert J. Ross

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Contributions from an Industrial Research Engineer

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Lumber Testing and the Machine Stress Rating Process

By the 1960s, research had shown that the intrinsic material property modulus of elasticity (*E*) is correlated with lumber strength (Hoyle 1961; McKean and Hoyle 1962; Senft et al. 1962). The macro-quantity, stiffness, being machine measurable and related to *E*, led to the development of various types of machinery for testing lumber stiffness, and the sorting of it into machine-stress-rated (MSR) lumber grades. More history and details of the MSR process were described by Galligan and McDonald (2000) in their update and revision of an earlier report (Galligan et al. 1977). Further interesting history was provided by Washington State University Professor Robert J. Hoyle at a workshop on machine stress rating (Hoyle 1981). That history is linked here because it may otherwise be difficult to obtain. Additional perspective about the field of wood products testing is provided in a more recent report (Ross 2015).

The C-L-T (Continuous Lumber Tester), which is the forerunner of the machine that today provides the fastest accurate production-line measurement of bending stiffness, was patented and prototyped by Keller of Potlatch Forests, Inc., in Lewiston, Idaho, USA (U.S. Patent No. 3,196,672) (Keller 1965). Industrial Sciences in Portland, Oregon, USA, and then Irvington–Moore in Tigard, Oregon, USA, manufactured commercial machines based on the Keller patent. The C-L-T consists of a series of rollers that propel and cause the lumber to be bent in the least stiff (flatwise) direction, first downward and then upward, as each piece progresses longitudinally through it.

In its day, the C-L-T was the fastest and most accurate production-line equipment used in the production of MSR lumber due to three basic design features. First, the bending is accomplished with load-measuring rollers whose axes are fixed in translation. Thus, the stiffness is a measure of the bending force required to achieve a fixed bending deflection. In contrast to the alternative of measuring the deflection caused by a fixed applied force, this largely eliminates the inertial effects caused by the translating load roller used in some competing equipment that attempted a fixed loading force. Second, there are two bending sections, each 1,220 mm (48 in.) long; the first bends the lumber downward and the second upward. The average from the second measurement with a delayed measurement from the first is taken as the result for that 1,220-mm length, thereby correcting for naturally occurring bow of the lumber that is almost always present to some degree. Potential grade category from the machine is based on both the average and the lowest of these measurements over the board length. The third basic design feature isolates each bending span with multiple rollers at the span ends. These rollers clamp the lumber and reduce effects of dynamic transverse motion of the lumber external to the spans as it enters and exits at production speeds. Final grade category is based on the machine stiffness measurements and visual characteristics of the piece.

Competing production-line equipment did not have all three basic C-L-T features, and these machines were used primarily at low speeds or in the laboratory.

The C-L-T was installed in several locations in the early 1970s. However, in its early days, the C-L-T was largely ineffective because its data processing system was inefficient. Among these machines languishing in the mills, one was at Frank Lumber Company in Mill City, Oregon, USA. There, the marketing manager, Len Moyer, recognized the potential marketing and use advantages of MSR lumber.

Moyer teamed up with the owner, Ed DeKoning, of Irvington Moore, then the manufacturer of the C-L-T, to find someone who could solve its data system problems. They found James D. Logan, an instructor in the Electrical Engineering Department of Washington State University in Pullman, Washington, USA. Logan had previously developed an E-computer system based on a U.S. patent by Pellerin and himself (U.S. Patent No. 3,513,690) (Pellerin and Logan 1970) and described elsewhere (Pellerin 1965) to measure *E* of a beam from its transverse vibrational characteristics and other parameters. (In 1972, Logan, DeKoning and Pellerin founded Metriguard Inc. in Pullman, Washington, USA. In 2017, Metriguard Inc. was purchased

by Raute Corporation of Lahti, Finland. Metriguard still operates from Pullman, but now it is known as Metriguard Technologies.)

After numerous visits to Frank Lumber Company, Logan retrofitted the C-L-T there—as well as those at several other mills—with an entirely new data system. This new data system used robust electronic load cells in place of force measuring rings to measure bending force in each bending span of the C-L-T. In this new design, which proved to be both reliable and accurate at the speeds required, Logan also used integrated circuit technology that was maturing with the space program.

MSR lumber became a reality by the mid-1970s because of its availability from functioning equipment and recognition of its advantages by producers of engineered products such as roof trusses, glulam beams, and parallel chord trusses. However, accuracy and reliability questions remained, and MSR lumber production needed a more formal quality control (QC) process than what the individual mills were using.

In 1978, Bechtel compared *E* measurements from an E-Computer with average *E* measurements from the C-L-T at Frank Lumber Company. Logan (1978) used Bechtel's results, scatter plot, and linear regression in his presentation (also fig. 10 of Bechtel (1982), which describes other details of the MSR grading process at that time). The plot and regression show an R^2 value exceeding 0.97. In his paper, Logan noted that the E-Computer method of measuring *E* has proved valuable in estimating the potential value of the MSR process to a lumber mill.

An early laboratory device developed by Stan Pelster (similar to a device sold by Metriguard Technologies, Pullman, Washington, USA, as the Model 440 Static Bending Tester) measures *E* with a dead load applied at the third points of a 1,220-mm (48-in.) bending span. The *E* when averaged over three or four locations along the lumber length compares well with the C-L-T average *E*, and R^2 values typically exceed 0.97 (Bechtel 1981c).

In 1978, Warren presented a procedure known as the cumulative sum, or just CUSUM, procedure for tracking and maintaining acceptable levels of quality in MSR lumber grades as produced at mills (Warren 1978). As adopted for use, a small sample, typically 10 pieces from every shift of production, for each grade and size combination is randomly selected from the MSR grade-sorted output and checked with off-line equipment for both bending *E* and strength. Whereas the production-line C-L-T and the off-line Pelster type of tester measure *E* in the flatwise direction, the QC equipment verifies *E* and strength in the edgewise direction. (Bendtsen and Youngs (1981) state that "There appears to be little difference in strength predictability from using either *E* measured flatwise or edgewise. Commonly, machines utilize flatwise loading because large, more easily measured deflections can be obtained at low stress levels, thus avoiding damage to the lumber. Flatwise loading also allows flexibility in adjusting to different widths. Edgewise loading is possible, but requires greater measurement sensitivity because of the smaller deflections.") From these tests, the CUSUM procedure can show that the 5th percentile (the value below which 5% of the population exists) of both *E* and strength in edgewise bending meet the grade requirements. In addition, the population mean value of *E* must be at least as high as the value assigned to the grade. The grade mark applied to the lumber shows both *E* and maximum extreme fiber stress in bending that may be used in design for that grade of MSR lumber. The assigned grade-mark stress value is intended to be a factor, typically 2.1 in North America, below the actual 5th percentile of the grade. This is to accommodate effects such as duration of load and includes a safety factor.

In addition to off-line QC of MSR lumber in bending, some lumber producers perform QC in tension using the CUSUM process to verify that the 5th percentile of tensile strength meets grade requirements. If QC in tension is performed, a maximum design tensile stress value may be placed on the grade stamp as well as bending *E* and stress values.

By statistical chance, the CUSUM process will sometimes indicate that the process is out of control, when in fact it is in control. An intensive sampling procedure can show that the process is in control. If it does not, then the lumber graded since last in control must be regraded after the process is back in control, either by correcting machine malfunction or by increasing machine grade thresholds.

At the same conference at which Warren described the CUSUM QC procedure that has since enjoyed widespread use, methods for estimating percentiles of a distribution were presented (Bechtel 1978). These methods, although useful, are not used in the QC process for MSR lumber production. The estimation of lower percentiles has always been an issue in testing of wood-based structural materials because of the wide variability of their properties. In particular, the designer must be cautious to keep design loads below the low end of a strength distribution. Sharp (1988) expressed concerns regarding the tensile strength of some MSR graded lumber. Unpublished notes (Bechtel 1988b) partially addressed these concerns.

If every piece of lumber in production is subjected to a proof load test, it has been shown that it can be economically feasible to break as much as 10% or more of a typical population of lumber produced (Bechtel 1983). By removing these low-quality pieces from the distribution, the lower percentiles of the distribution are increased, thereby increasing the value of the remaining material.

The form of property distributions for various wood populations has often been of concern. Often these have involved the shape of probability density functions.

However, when the lower tail of the distribution is of primary importance, as it is for strength distributions, the distribution shape is usually immaterial except in how it influences the lower tail. A simple procedure for estimating the integral of a probability density function known as the cumulative distribution function has been found useful (Bechtel 1981b). In the case of strength testing, where only the lower tail is important, it is not necessary to break every piece and learn the entire distribution. It is necessary only to estimate the lower tail of the distribution, and strength testing only up to and perhaps a little beyond the value of interest is sufficient.

Comparisons of results from different types of testing apparatus are important in determining the accuracy and reliability of the equipment. As noted above, *E* from the C-L-T correlates well with *E* either from an E-Computer or from a Pelster-type of tester.

Measurements should be repeatable. If a machine does not yield repeatable results from more than one test of the same specimen, then its accuracy may be questioned. For example, one can test each of *n* pieces of lumber in the C-L-T *m* times and gain an indication of the measurement repeatability. A study of this issue determined that from an efficiency standpoint, it is better to use fewer pieces of lumber and increase the number of times each is tested; that is, small *n* and large *m* (Bechtel 1993). However, in the C-L-T, rollers press the lumber into a bending configuration and propel it through the machine. A small amount of wood fiber compression occurs at roller contact points so that testing alters a tested specimen slightly. To avoid a cumulative effect, it is better to use small *m* and large *n*. By testing each piece just twice, two being the smallest value of *m* for repeatability testing, minimal change is observed in the tested pieces. In the C-L-T, a 30-piece sample has proved sufficient; that is, $m = 2$ and $n = 30$. For other types of measurements, a different conclusion might be reached.

Logan of Metriguard used the repeatability analysis described above and developed a program based on it that some MSR producers have used to good effect. Data from mill tests are analyzed, and the results are presented to the mill. This is particularly useful for a mill because it allows the mill to compare its machine performance, not only with itself at previous times, but also with other machines operating elsewhere—all while maintaining confidentiality among the mills.

In 1995, a new machine from Metriguard largely made the C-L-T obsolete (U.S. Patent No. 5,503,024) (Bechtel and Allen 1995; Bechtel et al. 1996). This successor machine, known as the Model 7200 or H-C-L-T (High Capacity Lumber Tester) was developed using the accumulated experience of Metriguard personnel over some two decades of selling, servicing, rebuilding, and modifying the older C-L-T. The H-C-L-T is capable of speeds exceeding 15 m/s (3,000 ft/min) and can receive lumber in-line directly from all except the very highest speed modern planers. By design, when compared with the older C-L-T, it is inherently more robust and accurate at high speeds, and it is simpler to maintain.

Bending stiffness, or *E*, is still the single most important measurement in sorting lumber for its structural value. Along with *E*, visual characteristics such as edge knots, wane, and planer skip are used to determine the MSR grade. In recent times, these characteristics come from optical or other sensors; in the past—and sometimes still today—a human visual grading expert performs that task.

Local variation in wood properties, such as *E*, density, grain angle, and the location of these properties on a board, can affect its strength. Various optical methods, X-ray determination of density variation (U.S. Patent No. 4,941,357) (Schajer 1990), and grain angle measurements have been proposed and/or used to improve the sorting of lumber into structural grades.

Bending Test Span Length

E measured on a short span is a better predictor than that from a long span for bending and tensile strength of lumber (Corder 1965; Orosz 1973; Oscarsson et al. 2014). In a 1990 meeting, Bechtel (1990b) presented features of the C-L-T; a proponent of a competing machine conceded accuracy and speed but claimed better resolution of *E* along the lumber length because his machine operated with a shorter bending span (900 mm). With development of the span function concept (Bechtel 2007), that claimed advantage was refuted. Bechtel and Allen (1995) discussed the new HCLT and illustrated with a figure showing span functions that gave better length resolution with 1,220-mm spans and clamp-roller end supports than competing equipment with 900-mm spans and simple end supports.

A direct measurement of *E* on spans much shorter than now used has been impractical with bending equipment. Increased bending force relative to deflection when using shorter spans causes measurement precision to suffer from irregularities at the lumber surfaces contacted by rollers defining the deflection. Compression of wood fibers perpendicular to grain at roller contact points, debris left on the wood surface, or other lumber surface irregularities cause increasingly greater discrepancies in deflection and consequent *E* measurement noise. This was alluded to by Bendtsen and Youngs (1981) in their discussion of flatwise versus edgewise bending and the difference in stress for a given deflection. In the future, we may see optical methods become useful for measuring small deflections. For those interested in pursuing this potentially very useful field, Goodman (2017) is an excellent text on Fourier optics and would be a useful starting point.

Other measurements (X-ray, grain angle, optical) can add local detail about wood quality useful for estimating

strength. Stress waves may also provide some detail, but more research will be required to overcome problems of reliably coupling stress waves into and out of the wood at production speeds to obtain local detail along the board length. Even so, the stress wave method has proved useful in the production-line for veneer testing (U.S. Patent No. 4,201,093) (Logan 1980; Uskoski et al. 1993) and in a number of other applications (Ross 2015; Chang et al. 2019). (Metriguard Technologies, Pullman, Washington, USA, produces veneer grading equipment based on use of stress waves.)

Local *E* Estimation

Short of a direct measurement, can we estimate local *E* from bending measurements? Here, we define "local *E*" as the *E* for spans shorter than those that can be measured practically with a direct bending test—and, yes, we can estimate local *E* by processing the available sequence of *E* measurements along the length of a board.

Present production-line equipment assigns each measured *E* to a location then at span center on a tested board. As the board moves longitudinally through the span, the equipment assigns a sequence of measured *E* values to a succession of span center locations along the board. In this way a sequence of measurements is assigned to a sequence of locations along the board between half the span length from its leading end to half the span length from its trailing end.

Each measurement clearly is not determined by just the one local *E* value at the center of the measurement span. Rather, the measurement is a composite value from all locations along the board within the bending span, and clearly not all values contribute equally. Intuitively, values near the ends of the span will not contribute as heavily as those near the center. If a measurement is identified only with the local *E* at span center, then contributions from this measurement to other local values are largely wasted. A weighting function showing how the local values in the span contribute is needed as well as method for using those contributions. The sequence of measurements may be considered the result of a mechanical filter applied to local values along the board length. The mechanical filter properties are determined by the bending span configuration, and the goal of local *E* estimation is to undo the mechanical filtering by appropriately processing the sequence of measurements.

In practice, production machines electrically filter the *E* signal to reduce measurement noise that is always present, such as from machine vibration and lumber surface imperfections. The filtering brings a type of average of neighboring *E* values together into each result, thereby implicitly assuming that neighboring *E* values are much the same, a reasonable assumption and necessary to reduce measurement noise. This necessary electrical filtering is a local effect and is in addition to the undesirable mechanical filtering.

The weighting function mentioned above defines the mechanical filter properties of the bending span. This function, called "span function," is shown to work with the reciprocals of *E*, which we call compliance. That is, compliance is 1/*E*, and local compliance is 1/(local *E*). The first weighting function for this purpose was alluded to and presented in a workshop (Bechtel 1981a) and then later more formally (Bechtel 1985). Local compliance values are linearly, but not equally, weighted to yield measured compliance, that is, the reciprocal of measured *E*. For a simply supported, center-loaded bending span, the weighting function is cusp shaped, beginning at zero from one span end to maximum at span center and then falling to zero at the other span end. The form of this cusp is a two-piece quadratic, first up and then down. The 1985 presentation (Bechtel 1985) incorrectly applied this weighting function, since called "span function," to the C-L-T—incorrectly, because the spans of the C-L-T are not simply supported. A method for computing the span function for a general system of supports, including the clamp-roller supports of the C-L-T or H-C-L-T, was described years later (Bechtel 2007).

Although Bechtel (1985) required the span function for estimating local *E*, it also seems to largely explain measurement differences when different types of loading configurations are used, such differences sometimes determined experimentally (for example, Paulo (2018)). Span functions show how local values are weighted into the measurements. When different bending configurations with different span functions are used, one could predict the differences in results depending on the uniformity of each tested board.

For the 1985 presentation (Bechtel 1985), Bechtel and colleague James R. Allen made bending *E* measurements on a 38- by 89-mm (2 by 4) board at a sequence of locations along the board with a simply supported, center-loaded bending span of 1,220 mm. Recognizing that the measured compliance function can be written as the convolution of the local compliance function with the span function, we applied the complex convolution theorem of the Fourier transform (Oppenheim 1989) and obtained the Fourier transform of the local compliance function by division. Then, in theory, the local compliance function can be estimated by inverse Fourier transform. Because the data are discrete, the discrete Fourier transform was used (Bechtel 2019c; Oppenheim 1989). In practice, as is usual with such operations, noise was a significant issue. Extensive measures were used for noise reduction as well as methods to wrap the ends of the limited data stream. The figure showing the result was not realized in time to be included in the proceedings record (Bechtel 1985), but it was presented at the conference and is attached to the linked reference. Although impractical due to the extensive computations required, the result showed that local *E* can be estimated from bending measurements. A better determination of knots

and their effect on *E* is seen with the local *E* result than with the original measured data sequence.

Methods other than the Fourier transform method have since been described to obtain local *E*. A second method used a Kalman filter (U.S. Patent No. 7,047,156) (Bechtel et al. 2006, 2007) and is more conducive to implementation than the Fourier transform method.

A third method uses straightforward linear algebraic processing (Bechtel 2009). The most recent reference for the third method (Bechtel 2018) discloses details of the proprietary method that achieved results reported earlier.

The results shown in the references are for simply supported, center-loaded bending spans. The method applied to the clamp-roller spans of the C-L-T and H-C-L-T would process the data similarly. A computational detail will require additional bookkeeping to track at least three different span functions as a board engages more and then fewer rollers when it first enters a bending span, completes it, and then exits it. Strictly speaking, five different span functions apply for an H-C-L-T and seven for a C-L-T, but in practice, there is not much difference between them except for a dominant three.

This third method achieves its result by using a vector of Lagrange multipliers (Kaplan 1952) to minimize a measure of dispersion among the infinite possible sets of estimated local components, each set of which satisfies an underdetermined algebraic system of linear equations obtained from the measurements.

None of these three methods (Fourier transform, Kalman filter, or algebraic) has been used in the production line, although all three give similar results for local *E*. Both the second and the third of these methods are implementable at production speeds, but the third (algebraic) is simpler to grasp.

The advantage of processing the measured data to yield local *E* is made clear by the following summary of salient points:

- The change from present method is primarily in software, and many software details are available with general purpose programs (for example, The MathWorks Inc. [no date]).
- All the measurements made while a local length of the tested board is within a test span contribute to its local *E* estimate. It does not make sense to use just one of the measurements for this purpose and discard the others, as in present MSR implementations, particularly now that computer processing speeds are available for real-time analysis.
- Some preliminary electrical filtering (averaging) of measurements is still required to reduce measurement noise. By taking this filtering to an extreme, the computed local *E* profile is practically identical with the measured *E* profile, but without as much measurement noise. This result can make implementation a smooth and painless process. First, start with extreme filtering designed to give the same estimated local *E* profile as the present measured *E* profile. (By itself, this could improve yields by reducing downgrading caused by noise in measured *E*.) Then, gradually reduce the amount of filtering and reduce the grade thresholds at the same time. Grading rules allow efficient small reductions in thresholds.
- A question is always raised: If local *E* estimation causes local reductions in the *E* profile along a board, will that cause more boards to be downgraded? This would occur except that the grade thresholds are also lowered. More boards that do not have significantly low local *E* values are retained in higher grades. To catch and fail the boards with low local *E* values, the present system must operate with higher than necessary grade thresholds. Local *E* estimation can catch and remove the bad actors even with lower grade thresholds because the low local *E* values are no longer masked by neighboring higher *E* values. Overall, it is anticipated that the increased accuracy of local *E* determination will increase value of the product mix.

Further Local *E* Research Possibilities

Local *E* estimation using the preferred algebraic method described in the previous section depends on a sequence of bending measurements that yield a set of equations as described in the literature (Bechtel 2009, 2018). Each equation relates a measured compliance to a linear combination of local compliances. Coefficients applied to each local compliance come from the span function for that measurement. For each measurement, a local compliance is at center of a bending span, but local compliances near the board ends cannot be at the center of any span. Consequently, there are fewer measurements than local compliances, and the algebraic system of equations is underdetermined. From the infinite number of solutions, the method finds the one that minimizes a measure of dispersion.

Bending tests suffer from only very small contributions to measurements from local values near board ends, so these local values are not well estimated. Other types of bending spans have different span functions, and span functions can be deduced for non-bending types of measurements. Some longitudinal vibration and stress wave testing methods weight local elements along a board equally. So, it seems reasonable to assign a uniform weighting function to that type of testing. By appending the appropriate equations from other measurements to the linear system of equations, additional estimation precision could be attained.

With enough additional equations from other measurements, the linear system of equations could become overdetermined with no exact solution. In that case, a solution with least square error could be determined much like solutions are obtained from global positioning systems that use timing information from multiple satellites. A brief section below discusses solution of linear equations.

Length Effect

In testing pieces of lumber to failure in tension, a weak-link theory and testing indicate that the tensile strength of long pieces is not as high as it is for short pieces (Taylor and Bender 1991). Statistics of Weibull distributions are often used to quantify this effect. The weak link theory can be modified to address the idea that there is correlation of local strength properties along the length (Bechtel 1988a, 1992).

Transverse Vibration E-Computer

Early use of the E-computer raised a question for which there seemed to be no answer: How do the local *E* values along the length of a board influence the measured result? For example, how does a knot with different properties than clear wood influence the result differently depending on where it is located in the board?

Using an approach with the E-computer similar to that used with bending test configurations to determine span function, Bechtel (2017) deduced span functions for the E-computer. (This reference has not been thoroughly reviewed by others.) Because it affects the vibration dynamics, mass density along a board must also be considered as well as local *E*. The E-computer method requires the board weight as an input, and usually the weight is approximated as double the measured weight at just one end. This simplifies the apparatus, and the resulting error is generally deemed acceptably small. However, the results are different, and the reference considers both situations. A section showing the arithmetic on which the E-computer depends is included because it is necessary for the derivations.

The transverse vibration nondestructive test can also be used to determine the damping characteristics of materials. A NASA reference publication (Spera et al. 1990) reported the use of a transverse vibration E-Computer to study damping characteristics of laminated Douglas-fir/epoxy lumber specimens from an effort led by Bechtel.

Bechtel (1990a) provides a description of terms sometimes used with vibrational analyses.

Grain Angle Measurement

Stiffness and strength in bending and in tension are heavily influenced by grain angle (FPL 2010). McLauchlan et al. (1973) described a grain angle measurement method based on dielectric properties of wood (James 1975). Bechtel developed those ideas into a measurement device sold by Metriguard as the Model 5100 Grain Angle Indicator. The equipment was bulky, required mechanically rotating electrodes, and was used in research but not in a production environment. Later, a stationary electrode version, the Model 520, was developed and described in U.S. Patent No. 4,972,154 (Bechtel et al. 1990a) and elsewhere (Bechtel et al. 1990b).

Although the literature describes the stationary electrode technology in detail, this technology has been misunderstood and misrepresented (Steele and Kumar 1996). The stationary electrodes do not cause a rotating field as did the rotating version. Rather, the stationary electrode method begins with a defined reference direction (typically the main lumber axis). Multiple electrodes are rapidly switched electrically between polarities of an applied voltage and cause different sets of electrodes to be grouped together with the same polarity during different time intervals. In a first interval, an electric field probes in one direction to yield a signal proportional to the sine of two times the grain angle. In a second interval, the field probes in another direction, to yield a signal proportional to the cosine of two times the grain angle. Division of the sine signal by the cosine signal removes the proportionality factor to obtain the tangent of two times the grain angle. An inverse tangent operation followed with division by two gives grain angle. The result is an accurate measurement of wood fiber direction, which, within limits, is independent of spacing from the electrodes to the wood surface.

Bechtel and Allen (1987) used a grain angle indicator to measure grain angle on a 1-cm grid over a 70-cm length on the surface of each piece of a 24-piece lumber sample. The pieces, selected at a local lumber yard, were loaded with knots. Bending *E* was measured on a simply-supported, center-loaded span of 122 cm centered on the 70-cm length of grain angle measurements. Then each tested section was loaded to failure in a Metriguard Model 401 Tension Proof Tester. Several methods were used to estimate tensile strength based on *E* and grain angle measurements. Results showed improvement in strength estimation (U.S. Patent No. 4,926,350) (Bechtel and Allen 1987, 1990). The best approach using multiple linear regression of tensile strength on both *E* and a number derived from grain angle measurements yielded $R^2 > 0.91$.

In reviewing a manuscript for a report by Geimer et al. (1993) on using a grain angle indicator to determine amount of flake alignment in flakeboard, Bechtel suggested that Mardia's statistics of directional data (Mardia 1972) could be used to indicate the amount of alignment. The paper was modified to describe that method; however, much more could be done in an implementation. For example, the alignment of different layers could be investigated with different appropriately sized sensor electrodes. This remains a potentially fruitful field for further research.

Ancillary Topics

Discrete Fourier Transform

The Fourier transform has been of interest for many years because it represents functions in terms of their frequency content. The development of high-speed digital computers now available at reasonable cost has revolutionized frequency analysis methods with use of the discrete Fourier transform. Efficient algorithms, generally known as fast Fourier transform algorithms, for implementation of the discrete Fourier transform are in widespread use. However, the terms fast Fourier transform (FFT), Fourier transform (FT), and discrete Fourier transform (DFT) are often used interchangeably, and they are not the same. The relationship between the FT and DFT was described by Bechtel (2019c) in an attempt to reduce this confusion. Briefly, the FT operates on a continuous function, whereas the DFT operates on sampled data. The domain changes from being a continuum to a set of numbers that are samples of a continuous function at discrete points of its domain. If samples of the function are sufficiently close together, the DFT usefully represents the FT. If not, it is known that aliasing can occur in the DFT. Aliasing is a concept where one frequency masquerades as another.

The DFT and its inverse are developed as a pair to show their similarities. Tradeoffs among frequency resolution, sampling interval, number of sample points, and represented length (period) in both the original and frequency domains become evident.

Linear Equations and Singular Value Decomposition (SVD)

Bechtel (2019a) may provide helpful insight to the topic of solving a system of linear equations. More comprehensive expositions are available (Strang and Borre 1997; Strang 2005). Understanding of this topic is key to the method for local *E* estimation.

Projection

Bechtel (2019b) may provide helpful insight to projection onto a subspace, another useful topic for the solution of linear equations. Projection is covered in more detail by Strang and Borre (1997) and Strang (2005).

Concluding Comments

As noted, the topics included in this publication are those that have surrounded Bechtel's work on the research, design, and development of modern test equipment used by the forest products industry. The referenced papers address only a small part of the broad spectrum of issues important to wood products testing, but they do address some topics not covered well elsewhere. Many important references by others are not included, although some of them can be found in the reference lists of the papers cited here. The links to unpublished or otherwise difficult to obtain references will be useful to those working in the forest products arena by making these references easily obtainable.

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(*Links to supplemental materials in this list of references open documents embedded in this file.*)

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