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Review

Non-Destructive Lumber and Engineered Pine Products Research in the Gulf South U.S. 2005–2020

R. Dan Seale, Rubin Shmulsky * and Frederico Jose Nistal Franca

Sustainable Bioproducts Department College of Forest Resources/Forest and Wildlife Research Center, Mississippi State University, Starkville, MS 39762, USA; rds9@msstate.edu (R.D.S.); fn90@msstate.edu (F.J.N.F.)
*   Correspondence: rs26@msstate.edu; Tel.: +1-662-325-2116

Abstract: This review primarily describes nondestructive evaluation (NDE) work at Mississippi State University during the 2005–2020 time interval. Overall, NDE is becoming increasingly important as a means of maximizing and optimizing the value (economic, engineering, utilitarian, etc.) of every tree that comes from the forest. For the most part, it focuses on southern pine structural lumber, but other species such as red pine, spruce, Douglas fir, red oak, and white oak and other products such as engineered composites, mass timber, non-structural lumber, and others are included where appropriate. Much of the work has been completed in conjunction with the U.S. Department of Agriculture, Forest Service, Forest Products Laboratory as well as the Agricultural Research Service with the overall intent of improving lumber and wood products standards and valuation. To increase the future impacts and adoption of this NDE-related work, wherever possible graduate students have contributed to the research. As such, a stream of trained professionals is a secondary output of these works though it is not specifically detailed herein.

Keywords: nondestructive evaluation; pine lumber; modulus of rupture; modulus of elasticity; mass timber; acoustic velocity; transverse vibration; structural lumber; engineered wood products

1. Introduction

In an ongoing effort to enhance forest sustainability and utilization, nondestructive evaluation (NDE) research is permeating into an increasing number of applications. At this stage, this type of research is often more applied than basic. That is, it seeks to solve current and pressing real-world problems at hand. A combination of federal-level (mainly through the U.S. Department of Agriculture and Department of Interior), state-level (through the state of Mississippi), and commercial/industrial interest and funding supports NDE research. This manuscript provides a review of the research stemming from these partnerships. The purpose of the manuscript is to pull together and summarize the findings of this targeted NDE work to help scientists and practitioners increase, improve, and adopt these types of technologies.

In short, NDE seeks to predict how stiff or strong an individual member will be. While the ultimate strength of solid sawn lumber is more variable than that of composites, the prediction of each's mechanical properties can be improved with the application of NDE. As basic forms of NDE are well-described elsewhere, they will be mentioned and discussed herein with the assumption that the reader has some level of familiarity with their basic underpinnings.

For structural purposes, wood and other building products must have safe and reliable performance. There is a plethora of building codes, design and testing standards, and materials assessment/use guidance that make wood and bio-based construction one of, if not the single most, cost-effective building material for residential and light commercial construction. Ultimately, wood, wood-based, and bio-based products typically provide the highest utility value on a stress per cost (in terms of Pascals stress per U.S. Dollar). When reduced to these terms, wood, wood-based, and other bio-based products generally

come out on top. This position, perhaps more than any of the other often touted attributes (sustainability, aesthetics, environmental concerns, availability, workability, etc.) pushes the notion that wherever possible—people choose to build with wood. Financing and depreciation schedules of home and other commercial structures is often in the order of 30 years. As such, cost sensitivity is high and maximizing the utility value of our U.S. private residential homes is paramount.

When structures are designed, constructed, paid for, and put in service, they are intended to be at or near their design loads for extended periods. By maintaining in-service loads at or near those associated with design, the individual member and the entire structure is able to perform in a safe, predictable, and reliable manner. This notion assumes that the mechanical properties of the individual members that comprise the structure are assessed accurately. By and large, there is non-trivial conservatism in the classic prediction and assessment of the performance of wood and wood-based products.

Classically, for structural evaluation of sawn products, one begins with a notion or idea (generally based on mechanical testing) of the strength and stiffness values of clear wood. Statistically, for strength, both the mean and the distribution are examined in an effort to estimate the fifth percentile. Then, a variety of reduction factors may be applied, such as load duration, uncertainty (or safety), grade, size, moisture, species group, and actual density. Additional property assessment can be developed via in-grade or full-scale testing. These schema assure that not only are 95% of the individual pieces as strong or stronger than the fifth percentile but that the vast majority are very much above it. Because there is much variation among individual members, particularly for solid sawn members, very large portions of this 95% are much stronger (often two, three, or four times as strong) as that at the fifth percentile.

Through NDE, one can narrow the gap between the "safe" predicted strength and the actual strength. The broad result of NDE is better and more appropriate utilization of the forest resource. Though its adoption, as more accurate strength assessments become available and used, builders and engineers can build bigger, stronger, and more numerous structures from the lumber and products coming from the same timber volume or timber-land area. The implications for global forest conservation, sustainability, and service to a growing population are staggering.

The research shown below highlights a broad swath of NDE development and application. Most relate to new construction. Some relates to existing products in service or in-situ. Both have implications for improving forest sustainability. The longer the time any given product or structure stays in service, the fewer hectares of timber need to be cut in a given year. As the accuracy of predicted strength increases, more homes can be built and the basic needs of an increasing population can be met from the same timberland area. That type of philosophy provides great hope toward meeting the home and shelter needs of an ever-increasing global population.

The research highlighted herein has occurred as part of ongoing partnerships between federal, state, and private interests. This three-legged stool approach provides great stability and a high degree of accountability. Industrial and commercial stakeholder input has been gleaned throughout. Their input and guidance has helped steer the research toward the most pressing needs. The federal and state input and interest has assured that the work maintains broad interest and influence across the state, region, and national levels.

2. Fundamentals

Fundamentally, the interrelationships among specific gravity, stiffness, and strength are largely at the heart of NDE. As a means of monitoring mill production, quality, and timber resources over time routine stiffness evaluation often provides the best "reasonable" indicator.

Work with NDE tools at Mississippi State University accelerated in 2004 with the acquisition of a Metriguard E-Computer and a Fiber Gen HM200. The impetus for this change arose for the need to grade a pilot-scale, high-strength and stiffness-engineered

wood product that had no surface defects. There, NDE was used to evaluate both the finished product and the raw materials. While encouraging, these results were not sufficient to adequately grade the engineered product. Ultimately, an X-ray technology was used in conjunction with the NDE to determine on-grade product. The X-ray could spot low-density zones which impacted modulus of rupture (MOR) and the NDE tools accurately predicted static bending stiffness. Basically, the X-ray technology worked as an analog to knot allowances in solid sawn machine stress rated (MSR) and machine evaluated lumber (MEL). That work resulted in a report issued by APA The Engineered Wood Association in 2007 [1].

In work by Franca et al. (2021) [2], the modulus of elasticity (MOE) and modulus of rupture (MOR) of clear pine bending specimens, taken from full scale in-grade southern pine specimens after destructive testing, were evaluated. In that work, similar sampling and like testing protocols per ASTM D143 (2018) [3] were followed albeit approximately 50 years apart. In that work, the strength of the correlation between MOE and MOR of these small clear specimens cut from destructively tested full-scale specimens, appeared relatively constant over time with r^2 varying between 0.598 and 0.635. That said, the slopes of the linearly regressed line with MOE as the independent variable and MOR as the dependent variable changed over this five-decade interval. This finding suggested that MOE remained a relatively robust indicator of MOR over time. This finding also suggested that routine calibration and reassessment of the MOE to MOR relationship is necessary as one can trend away from the other over time. Specific gravity vs. MOR r^2 values ranged from 0.405 to 0.499 while r^2 values for MOR as a function of specific gravity plus MOE ranged from 0.64 to 0.76.

Idealizing the MOE and MOR relationships among perfectly homogeneous materials is routine. Applying these relationships to actual small clear specimens adds a level of variability. Then, applying these to full-size pieces of lumber adds an increasing amount of variability. To glean a better understanding of how NDE can be best applied to grading or performance assessment of graded lumber at a mill level, it seems appropriate to investigate NDE at the mill level prior to lumber grading. To this end, researchers have sampled structural lumber from varying production facilities. At a fundamental level, Anderson et al. [4] found that MOE and/or MOR may change at a given mill over time. This finding can perhaps be somewhat explained by raw material resource changes throughout the year. At wetter times of the year, logs are taken from higher and drier ground. During the drier summer time, loggers can pull logs from what might otherwise be wetter bottomland.

Given the historical complexity associated with describing the MOE and MOR population distributions of graded lumber, researchers have examined these properties from full lumber populations. That is, Owens et al. [5] have attempted to analyze and describe the MOE and MOR relationships and distributions in mill run lumber. There, mill run lumber describes all the specimens which make it through the dry kiln in a sound manner. After that, in a pine sawmill, lumber is planed, graded, and trimmed in a closely coupled sequence. Thus, pulling non graded lumber from kiln packages after drying provided the last such opportunity before grading. There, findings indicated that lumber distributions for MOE and MOR varied by mill. This finding greatly complicates the notion of using MOE to accurately predict MOR, particularly at the lower tail, that is, the statistical region from which design strength values are derived. Further research on the MOE and MOR relationships, particularly in the lower tails of the population (where it may matter the most) is found in work by Verrill, Owens, et al. [6–10]. To broaden the impacts and implications of this work, these analytical techniques related to fitting statistical distributions to MOR and MOE have been applied to mill run spruce and red pine lumber populations by Anderson et al. [11].

3. Dimension Lumber

In work by Dahlen et al. [12] both southern pine and Douglas fir were sampled. In that case, the MOE and MOR were correlated in 2 × 4 lumber from six pine mills (from the

states of Alabama, Arkansas, Georgia, Mississippi, and Texas) along with six Douglas fir mills (from Washington, Idaho, Oregon, and Canada) that were sampled. Neither of these was considered a production weighted sample however the geographical representation was widely reaching. All specimens were testing in bending per ASTM D198 [13]. In sum, 744 pine specimens were considered and the MOE to MOR r^2 value (adjusted to 15% MC) was 0.52. Similarly, 733 Douglas fir specimens were considered and the MOE to MOR r^2 value (adjusted to 15% MC) was 0.66.

Additional research on Douglas-fir and southern pine 2×4 s by Dahlen et al. [14,15] showed great variability among mills with respect to MOR variation and MOE vs. MOR correlations. In each case, variations were statistically significant at the $\alpha = 0.05$ level. These findings highlight the conservatism in developing global design values for an individual species. It also provides an impetus for implementing NDE, such as MSR or MEL, as a means of capturing the otherwise lost utility value of stiffer and stronger material at sawmills that convert high-quality timber resources.

Generally, it has been observed that mills with a wider range of raw materials, such as those mills that run both small logs and relatively large logs, see better MOR to MOE correlations. This finding seems to be because they produce a lumber with a wider range of density and a wider range of MOE. Often, this manifests itself as 2×4 and 2×6-inch lumber being manufactured from both the juvenile-wood center of small diameter trees (relatively weaker properties) and from the outside (jacket boards) of larger logs (relatively higher properties). This factor typically leads to a wider range of MOR values and thus their respective r^2 values increase. These findings suggest that if a given mill wishes to investigate NDE as a means of capturing utility value, that mill should to first evaluate their particular resource and if implemented, that mill will need to dial-in the performance of their equipment and routinely calibrate it. With respect to strength distribution, the wide variation in properties between juvenile wood vs. jacket board lumber often makes the 2×4-inch and occasionally the 2×6-inch sizes appear bimodal.

To enhance sample variation, Yang at al. [16] report sampling 490 pieces of #2-in grade lumber from mills in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas. A total of 31 mills were sampled. No more than 10 pieces per size (2×6, 2×8, 2×10, 2×12-inch) came from any one mill. There, r^2 values for MOE vs. several NDE technologies for this #2 grade (all 4 sizes combined) lumber were—average continuous proof bending MOE (0.85), transverse vibration MOE (0.90), longitudinal stress wave per Falcon A-Grader (0.82), longitudinal stress wave MOE value from Director HM200 (0.85), and longitudinal stress wave velocity per Director HM200 (0.63). In related work by Yang et al. [17], the relationship between NDE MOE vs. MOR was investigated for the same lumber sample. Not surprisingly, correlations were lower than that for NDE MOE vs. static MOE. MOR correlations for in-grade full scale pieces are knowingly more variable due to the inclusion of large localized strength reducing characteristics which may (or may not) be included in the area of maximum moment during the bending test. There, r^2 values for MOR vs. several NDE technologies for this #2 grade (all four sizes combined) lumber were—average continuous proof bending MOE (0.23), transverse vibration MOE (0.26), longitudinal stress wave per Falcon A-Grader (0.27), longitudinal stress wave MOE value from Director HM200 (0.28), and longitudinal stress wave velocity per Director HM200 (0.15).

To increase the robustness of additional research, Franca, T.S.F.A. et al. [18] and Franca, F.J.N. et al. [19] describe a method that led to a production of a weighted, in grade, pine lumber sample. There, the classic timberland growth regions are described and approximately 1223 pieces of 2×4, 2×6, 2×8, and 2×10-inch lumber were procured from 15 of the 18 growth regions. These specimens were then evaluated with NDE technologies and subsequently tested in static bending. NDE technologies included longitudinal vibration by Fakopp, Falcon A-grader, and Director HM200 and transverse vibration (both edgewise and flatwise) by a Metriguard Model 340 E computer. Results of the 2×4 and 2×6-inch sizes are reported in Franca et al. [20]. There, r^2 values for dynamic

MOE (that is NDE MOE) vs. static MOE ranged from 0.819 to 0.891. Similarly, r^2 values for dynamic MOE vs. static MOR ranged from 0.383 to 0.451. Results of the 2 × 8 and 2 × 10 sizes are reported in Franca et al. [21,22]. There, r^2 values for dynamic MOE (that is NDE MOE) vs. static MOE ranged from 0.76 to 0.92. Similarly, r^2 values for dynamic MOE vs. static MOR ranged from 0.17 to 0.32. From these findings it appears that the NDE technologies were less reliable in the wider dimension lumber (2 × 8-inch and 2 × 10-inch) as compared to the narrower specimens (2 × 4-inch and 2 × 6-inch). This finding may be because there is less variability among the wider dimension lumber, that it, it is generally cut from similar log resources. In contrast, the narrower dimension lumber is often more variable with some coming from small diameter-largely juvenile wood core-trees, while some comes from the outer material (jacket boards) of wider logs. This increased variability tends to improve MOR to MOE and MOE to NDE MOE correlations as there is a greater quality spread among all the specimens. Additional discussion and findings related to prediction of MOR by NDE in combination with other properties is provided in Franca, F.J.N. et al. [23].

Further improvement in NDE usefulness and accuracy toward lumber evaluation is continually being sought. In two works by Senalik et al. [24,25], fundamental wave analysis/signal processing was used to predict tensile MOE and ultimate tension stress (UTS). There, pine specimens were machined from in grade lumber. Specimens contained a varying range of growth characteristics. There, the r^2 value between dynamic MOE (alone) and UTS was 0.52. When additional parameters related to time-domain signal, energy attenuation, and arrival energy were added to the prediction model, the r^2 value increased to 0.71. This finding indicates that there is much information that can be gleaned by more in-depth wave analysis, all of which can potentially be automated, thereby enhancing the utility value of NDE technologies. Further, it is anticipated that the techniques described in these two manuscripts may ultimately be useful toward identifying anomalies (that is strength reducing characteristics) along the length of a given piece of lumber. If developed, this type of technology may enhance optimized and automated trim solutions during structural lumber production.

An overview of the commercial scale adoption and growth in machine stress rated lumber is provided in Entsminger et al. [26]. This reference details many of the practical and technical aspects of that a mill typically considers when considering adoption of NDE technology. It also details the overall growth in machine stress-rated lumber production as well information regarding production by size, region, Fb/E class, etc.

In addition to more traditional vibration and acoustic velocity as means of measuring MOE and assessing reductions in MOR, grain angle is long known to be detrimental toward structural lumber's mechanical properties. Commercially available technology can now measure lumber permittivity and subsequently estimate grain angle. Anderson et al. [27] report on work related thereto on mill run southern pine lumber. There, the overall relationship, as measured by Pearson's correlation coefficient, between grain angle and MOR was reported as −0.42. Further, correlations improved as grade (lumber quality) declined. This finding suggests that this type of technology has the potential to improve quality assessment in structural lumber particularly if used in combination with other NDE technologies. Further discussion of some of the fundamental grain angle investigations is provided in Bechtel and Ross [28].

4. Roundwood Dowels

Climate change appears to be causing greater variation in extreme weather events. In the U.S., the Gulf South region is heavily timbered. It is also highly susceptible to tropical storms and hurricanes stemming from or passing through the relatively warm Gulf of Mexico. As a result, wind or storm damaged timber is not uncommon. Fully damaged, broken, and twisted tree stems are rarely salvaged into usable logs. The costs and risks associated with getting them to the mill in a timely manner are high. That said, high wind events often only partially damage wood or forest tracts. Sometimes, high wind events

partially wind throw trees. The result (post-storm) may be fully upright or partially leaning trees, forest stands, or vast forests. While visually "normal" there may be inherent damage (in the form of ring shake or mild to moderate timber break). In some cases these may only become visible after sawing, after drying and planing, during peeling wherein the core separates from the log, worse yet after being put into service which invariably causes expensive claims and seemingly unnecessary consternation. Following hurricane Katrina (late summer 2005) a storm which damaged thousands of hectares of timberland research by Slay et al. [29] investigated the ability to use acoustic velocity to assess non-visible damage in small round stems that had been turned down to 4-inch diameter dowels. Dowels were selected for their uniform section and low potential for cross grain from end to end. There, the acoustic velocity in green wood dowels was measured and then the dowels were stressed in bending. This process was repeated at increasing stress increments. Of particular interest was the ability to use NDE to detect if each dowel had been stressed beyond the proportional limit and was thereby permanently weakened. The rationale was that if NDE could be employed in this manner, then a given processing facility could measure incoming raw materials and either deduct value as appropriate or merchandise damaged logs more appropriately.

In related work, Shmulsky and Snow [30] investigated the interrelationships of MOE, acoustic velocity, rings per inch (a surrogate for density) and MOR on 5-inch diameter pine dowels. In this work as well, dowels were chosen as their uniform section simplifies analysis while also maintaining a high degree of straight grain throughout the length. There, the combination of acoustic velocity plus rings per inch were strong predictors of MOE (r^2 values of 0.72 (green wood) and 0.76 (dry wood)). The best predictions for MOR used either acoustic velocity plus MOE (r^2 values of 0.45 (green wood) and 0.51 (dry wood)) or acoustic velocity, rings per inch, and MOE (r^2 values of 0.50 (green wood) and 0.53 (dry wood)). Given the added complexity of using three predictors versus two, the combination of acoustic velocity and MOE seemed like the most favorable choice of predictors.

5. Utility Poles and Crossarms

Wood utility poles remain the lowest cost solution for distributing electric power and utilities throughout the U.S. While other materials are used extensively, particularly in specialty applications, wood poles with their low cost, wide availability, and 30–50+ year life, remain the material of choice. Around two million new poles (either as new construction or line-rebuilding) are put into service each year. If one estimates 125 pole-class stems per acre then one can quickly surmise that approximately 16,000 hectares of land are required to grow these poles. At a 40 year rotation, one can project that 640,000 hectares of land (about the size of the state of Delaware) are continually associated with growing pole class stems. Thus, anything one can do to extend their service life relieves the pressure on this land area. To assess novel technology intended for in situ assessment of wood utility poles, a study of 50 specimens was developed by Seale et al. [31]. There, during routine 8–10 year infrastructure inspection, approximately 200 poles were selected for removal and replacement. Among these, 50 poles were identified for further study. These poles were tested via NDE in the field with the novel technology, removed from service, brought to Mississippi State University, tested via NDE again, and then tested to failure per ASTM 1036 [32]. Of these 50 specimens, 17 were reinstalled in the ground, the ground was compacted, and they were tested in an upright orientation. A total 33 of the specimens were tested horizontally in a dedicated utility pole testing fixture. Among all 50 poles, the r^2 value for the actual breaking strength vs. the predicted value was 0.56. This value is similar to that commonly observed with dimension lumber during manufacturing. For the 17 specimens that tested in the upright orientation (installed in the ground), the r^2 value between actual vs. predicted breaking force was 0.73. This finding suggested that the NDE technology showed great promise in potentially evaluating in situ wood utility poles during their requisite routine inspections.

Wood utility crossarms are produced to a national standard, ANSI O5.3 [33]. Based on a series of visual standards, these specialized industrial products either make the grade or are culled. There is a need for higher capacity arms in certain high load situations such as end-of-lines, generally as distributions circuit capacity is increased and as the electrical grid is hardened to improve resilience. Work by Catchot et al. [34] evaluated both Douglas fir and southern pine cross arms. There, manufactured cross arms of these two species were measured via varying NDE technology and then destructively evaluated. Both acoustic velocity and longitudinal vibration most accurately predicted MOR and MOE. Results also indicated that these technologies could be used to identify candidate stock for a premium type grade that would have superior mechanical properties as compared to the general on-grade population.

6. Portable/Smartphone NDE

To push NDE to the consumer level, researchers have developed a smartphone application that calculates lumber MOE (Franca et al. [35]). This work describes the development and accuracy of a program that uses either the smartphone microphone or its accelerometer to calculate the MOE of solid materials. While not robust and fast enough for the production setting, it is useful for builders and building contractors to assess their lumber particularly when trying to choose pieces for beams and headers. Furthermore, technology such as this can be helpful for assessing material performance over time, such as in the case of scaffold planking. Related work by Han et al. [36] investigated market acceptance and interest in this type of smartphone application

7. Hardwood Lumber

Hardwood lumber is widely used for flooring, stair systems, rail and guard systems, and others. In some of these cases it necessarily provides structural capacity. The building code(s) in the U.S. require specified strength and stiffness performance levels for structures and their various sub systems, such as stairs and guards. To meet these requirements, building products must have publically available bending strength and stiffness values. In the case of the grades, sizes, and species most often used in stair and guard systems, these mechanical properties are not readily available. As part of a study to investigate potential changes among red oak, white oak, hard maple, and yellow poplar lumber in these applications, NDE-related findings are reported in Turkot et al. [37]. This work is critical toward maintaining, and potentially growing, the markets for U.S. hardwoods that are to be used in load bearing applications.

8. Engineered Lumber

Yang et al. describe the production [38] and mechanical properties [39] of a novel type of engineered lumber that incorporated machine stress rated lumber stock at the extreme edges of structural beams. There, the machine stress-rated lumber, when applied to the extreme edges of beams, greatly improved the design bending strength of lower quality (number 3 grade) lumber. Further work related to NDE of cross laminated timber is ongoing at Mississippi State University. This work is geared to in plant or in-field assessment of bondline quality. This type of information is critically important for the quality control and quality assurance related to mass timber which ultimately minimizes its risk for failure and maximizes its uniformity.

9. Conclusions and Discussion

NDE has gained wider and wider commercial acceptance during the past three decades and research at Mississippi State University is pushing the technology toward increased adoption and application. There are a wide variety of NDE technologies and a great many ways in which they can be applied to real-world production or in-situ products and structures as a means of improving product valuation and structural assessment. It is anticipated that the coming decades will see:

- Greater use of NDE in mass timber/cross laminated timber production;
- Increased use by saw mills and other structural lumber producers;
- Improved means of identifying strength and stiffness reducing characteristics;
- Potential adoption of automated visual grading systems as candidates for producing machine stress rated lumber and machine evaluated lumber;
- Novel engineered composites that incorporate NDE in their manufacturing quality control and assurance;
- Additional field-based devices that allow contractors, engineers, builders, and others perform some level of NDE on wood members and structures either at the time of (or post) construction; and
- Development of wave analysis techniques to improve trim saw solutions.

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