# EVALUATING LOG STIFFNESS USING ACOUSTIC VELOCITY FOR MANUFACTURING STRUCTURAL ORIENTED STRAND BOARD

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**Abstract.** Oriented strand board (OSB) is an engineered panel product formed by layering strands of resinated wood in specific orientations into a mat, then pressing the mat at a high temperature to form a panel of desired strength and stiffness. OSB manufacturing facilities utilize small diameter logs from thinning operations and waste from harvesting. Considerable variation exists in the wood properties of the raw material and ideally the OSB industry would take advantage of such variation, however, it lacks the technology required to rapidly assess log quality on-site. Nondestructive evaluation (NDE) techniques based on acoustics have the potential to rapidly segregate logs in the field, however, the influence of acoustic-based log segregation on OSB panel properties is unknown. The aims of this project were to determine whether log quality affects panel properties and if acoustic NDE technology is a satisfactory tool for determining log stiffness before entering the manufacturing process. It was found that low-velocity (stiffness) logs produced panels with low stiffness whereas high- and medium-velocity (stiffness) logs produced panels with similar properties. The Director HM 200 was a satisfactory tool for determining log stiffness. Further studies are required to determine how to incorporate NDE tools into the manufacturing process.

***Keywords:*** Acoustics, log stiffness, oriented strand board, log sorting, log quality, engineered wood products.

## INTRODUCTION

Oriented strand board (OSB) is an engineered panel product formed by layering strands of resinated wood in specific orientations into a mat, then pressing the mat at a high temperature to form a panel of desired strength and stiffness. The mat consists of approximately 90–95% soft or hardwood, 3-8% exterior grade resins, and 1-5% wax products. OSB manufacturing facilities are able to utilize small diameter logs from thinning operations and waste from harvesting while maintaining equivalent strength and stiffness to plywood. Owing to the use of low-value raw materials OSB competes with plywood on a cost basis and in the early-2000s US production of OSB exceeded production of structural plywood (Howard 2002). In 2021, North American OSB panel production was approximately 25.5 billion square feet (Forisk 2021).

Using low-quality, small-diameter logs, some OSB manufacturers are able to produce high-quality, specialty products for high-end structural uses, such as I-joists, and engineered flooring and roofing systems. However, if low-quality logs with

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inherently low stiffness are used to develop high-quality specialty products, then manufacturing facilities must compensate for the low stiffness furnish with more expensive materials such as resin and wax to achieve desired product properties. Considerable variation exists in the wood properties of the raw material and ideally the OSB industry would take advantage of such variation, however, it lacks the technology required to rapidly assess log quality.

Interest in the area of nondestructive wood evaluation has seen the emergence of several new techniques: acoustics (Wang et al 2007), near IR spectroscopy (Schimleck and Evans 2002), and SilviScan (Evans 2006), which are suitable for the prediction of log quality, specifically, stiffness. Of the three technologies, acoustics has been favored for on-site evaluation owing to the development of robust, inexpensive, field-based tools (Huang 2000; Carter and Lausberg 2001; Chauhan et al 2006; Wang et al 2013; Schimleck et al 2019).

Log stiffness is derived from green log density, which can be measured but is often assumed to be constant (Schimleck et al 2019), and acoustic velocity. Several studies have used acoustics to evaluate log stiffness and have examined what impact log segregation, based on acoustics, has on sawn lumber grade recovery (Ross et al 1997; Carter and Lausberg 2001; Wang et al 2002; Dickson et al 2004; Grabianowski et al 2006; Raymond et al 2008; Wang et al 2013; Butler et al 2017; Simic et al 2019). However, few studies have examined the influence of acoustic-based log segregation on composite wood products. Ross et al (1999) examined acoustics for assessing the potential quality of veneer obtained from ponderosa pine (*Pinus ponderosa* Douglas ex C.Lawson) logs and found that a strong relationship existed between log and veneer nondestructive measurements. Carter and Lausberg (2001) also reported that several trials have been conducted to examine the effectiveness of acoustics, for segregating logs for veneer production. In a study based on logs from the Central North Island of New Zealand, high stiffness logs resulted in production of 51.9% premium DT veneer product, compared against unsegregated logs of only 24.1%. Segregation using acoustics resulted in substantially higher proportions of higher stiffness veneer being produced. Ross and Pellerin (1988) also found stress wave speed to correlate well with certain mechanical properties of wood composite panels. To the best of our knowledge no studies exist that report the effects of acoustic-based log segregation on OSB panel properties.

The objective of this study was to determine whether acoustic technology could be used to presort logs for manufacturing high stiffness OSB products. The overall hypothesis is that presorting logs using acoustic technology will give manufacturers a means of optimizing their current wood use by identifying high-quality logs for structural products.

## MATERIALS AND METHODS

### Sample Origin

This study was based on samples from the southeast Oklahoma-Arkansas area, where samples were taken from an area having a radius of approximately 250 miles. Wood having different origins, naturally grown shortleaf pine (*Pinus echinata* Mill.) and plantation grown loblolly pine (*Pinus taeda* L.), were investigated. Preliminary velocity measurements were taken on logs from different sites to determine how it varied. A minimum of 30 measurements from both natural and plantation types were taken. All baseline data were compiled, keeping the two growth types separate. Interquartile ranges and 95% confidence intervals for the mean were calculated using Minitab Statistical Software (version 15). Based on this information, three velocity groups (high, medium, and low) were identified for the plantation and natural groups. All measurements were in imperial units.

### Sample Selection

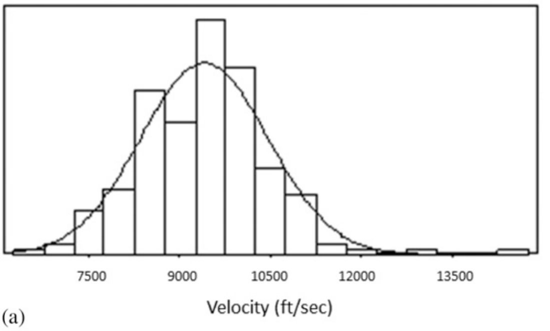
Trucks entered the manufacturing facility and stand locations along with plantation or natural type were recorded for identifying velocity trends by site. A grapple load of logs (approximately 5-10 logs) was unloaded from each truck and set aside in a pile (the truck continued further to complete unloading as standard for the manufacturing facility). Log lengths were measured in the pile as accurately as possible, and the Director HM 200 acoustic tool used to measure velocity. Logs were assigned to the appropriate velocity group and were marked with a sequential number. A total of 368 logs were tested for velocity with the distribution of velocities for logs from plantation and natural forests shown in Fig 1. The logs came from 72 trucks from 21 different counties in Texas, Arkansas, Louisiana, and Oklahoma.

Logs were spread out on the ground and measured a second time to record an accurate length. Velocity was also remeasured and if it was still within one of the target groups, the log was labeled with a color code (Table 1), in addition to the log number, and was sampled for further testing as follows:

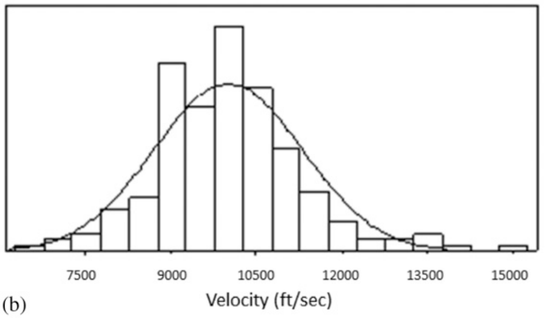
- The first 4-6" of wood was trimmed from the butt giving a clean surface for the Director HM 200 as well as to eliminate the air-dried butt;
- Two 1-2" thick disks were cut after the butt was trimmed. One was used for MC, age, and diameter determination, the second used for specific gravity determination;
- The following $2'$ of log after the disks were cut was sampled for clear lumber testing;
- Following the clear lumber sample, a $10'$ bolt was cut for OSB manufacture; and
- Sampling continued along the length of the tree in the same manner: 2" disks then $2'$ bolts, and finally $10'$ logs. Most of the logs sampled were long enough to provide 2-$10'$ bolts, 2-$2'$ bolts, and 3 sets of disks.

## Flake Manufacture

The $10'$ bolts were sent to the University of Maine (UM) for debarking, stranding, and drying. Debarking was done by hand using a draw knife once the logs arrived at UM, and then the debarked logs were sprayed periodically with




(a)




(b)

Figure 1. Distribution of velocities for logs from (a) plantation (186 logs) and (b) natural forests (182).

Table 1. Summary of stiffness groups.

| Source | Color code | Velocity group | Velocity min (ft/sec) | Velocity max (ft/sec) | # Logs sampled | Av. length (ft.) |
|---|---|---|---|---|---|---|
| Plantation | Red | 1 | 7480 | 8957 | 7 | 40.6 |
| | Green | 2 | 9416 | 11,089 | 11 | 38.6 |
| | Purple | 3 | 11,122 | 14,731 | 9 | 37.8 |
| Natural | Orange | 4 | 7054 | 8432 | 13 | 27.5 |
| | None | 5 | 8530 | 10,827 | 3 | 42.3 |
| | Blue | 6 | 11,089 | 14,961 | 7 | 30.9 |

water to keep them from drying out prior to stranding. Stranding was completed using a Carmanah 12/48 ring strander capable of processing logs up to 13" diameter to a target flake thickness of 0.025". Flake length was targeted at approximately 6", whereas width was difficult to control owing to variable log diameter, so only a visual target was used (acceptable or not acceptable). Prior to drying, fines (material less than 0.125") were screened out using an Acrowood Trillium Diamond Roll screen. A Koch Bros. Low Temperature Conveyor Dryer was used to dry strands to approximately 8-10% MC. Strands were passed through the dryer at 340°F at 3′ per minute, giving a 3.3 min residence time for the 10′ long dryer.

## OSB Manufacture

The strands (in approximately 50 plastic-lined Gaylord boxes) were sent to the Alberta Research Council (ARC) test facility located in Edmonton, Canada, for OSB manufacture. Strands were redried upon arrival at the ARC facility in a hot air box dryer to 8% MC. After drying, strands were batch blended in a coil blender and a liquid isocyanate resin was applied with a single atomizing head; emulsified wax was applied with an air atomization system at loadings typical to a high-strength OSB product. Three-layer panels were produced on a single opening hot oil press at 420°F with the surface orientation being parallel and the core orientation perpendicular, ie typical orientation for OSB production. After pressing for approximately 4 min, panels were trimmed to final size, density was calculated, and panels were allowed to hot stack overnight prior to OSB panel testing at a private testing lab.

## OSB Testing

Panels were tested according to Table 2. Properties evaluated were full panel stiffness in both the parallel and perpendicular strength directions (Panel flexure-QL-3), small sample bending for strength and stiffness (MOE and MOR, respectively, along with bending strength in parallel and perpendicular panel directions (FbS)), dimensional stability parallel and perpendicular (linear expansion ≤), and water absorption and thickness swell on edge (water absorption (ABS) and thickness swell (TS), respectively).

## Statistical Analysis

All log and full panel data analysis was performed using Minitab Statistical Software version 15 (Student edition). Dynamic MOE (DMOE) was calculated from the measured log velocities. Variables considered from the raw stem data were site location (site), inside bark butt diameter in inches (IBD), green and basic specific gravity (GSG and BSG, respectively), and tree age (age). All data were analyzed for relationships with either log velocity ($V$) or DMOE. All data were analyzed using naturally and plantation grown wood as separate groups.

# RESULTS

## Full Panel Testing

Full panel bending, panel flexure, was tested according to ASTM D 3043 method C (2000). A summary of the results by velocity group is shown in Table 3. Group 1, the low-velocity (stiffness) plantation group, gave parallel EI values from 423,683 to 507,755 lb-in$^2$/ft with an average of 468,460 lb-in$^2$/ft. In comparison, group

Table 2. OSB Panel testing matrix.

| Test | Method | Conditions (vel. group[a]) | Panels per condition | Samples per panel | Total samples |
|---|---|---|---|---|---|
| Panel flexure (QL-3) EI | ASTM D 3043-C | 6 | 7 | 2 | 84 |
| Small sample bending - MOE, EI, MOR, FbS | ASTM D 3043-D | 6 | 7 | 4 | 168 |
| Dimensional stability - LE | PS2 | 6 | 7 | 4 | 168 |
| Water absorption | ASTM D 1037 | 6 | 7 | 4 | 168 |
| Thickness swell | ASTM D 1037 PS2 | 6 | 7 | 4 | 168 |

LE, linear expansion; OSB, oriented strand board.
[a] See Table 1 for the six velocity groups.

4, the low-velocity natural group gave parallel EI values from 353,406 to 476,419 lb-in$^2$/ft with an average of 437,345 lb-in$^2$/ft. The high-velocity groups had similar performance with an average of 511,802 lb-in$^2$/ft. (range of 454,787 to 558,726 lb-in$^2$/ft) for plantation grown wood and an average of 519,783 lb-in$^2$/ft (range from 400,182 to 596,165 lb-in$^2$/ft) for naturally grown wood. Perpendicular EI results were similar for the plantation and natural groups. The middle velocity logs of the parallel and perpendicular EI groups of both growth types had slightly higher averages than the other groups with higher minimum and maximum values.

## Small Sample Testing

Small sample bending was tested according to ASTM D 3043 (2000) method D: three-point bending using an MTS universal test machine. A summary of results is given in Table 4. Plantation grown trees resulted in parallel small sample stiffness of $1.045 \times 10^6$ psi, with 441,042 in*lbf EI for the low log velocity group, a MOE of $1.193 \times 10^6$ psi, with an EI of 503,311 in*lbf for the middle group, and a MOE of $1.224 \times 10^6$ psi with a EI of 516,767 in*lbf for the high log velocity group. Naturally grown trees had similar parallel small sample stiffness with $1.023 \times 10^6$ psi, with 431,950 in*lbf EI for the low log velocity group, a MOE of $1.208 \times 10^6$ psi, with 509,773 in*lbf EI for the middle group, and $1.278 \times 10^6$ psi MOE with an EI of 539,283 in*lbf for the high log velocity group.

Perpendicular small sample stiffness ranged from 396,382 psi (167,224 in*lbf EI) to 355,637 psi (150,035 in*lbf EI) for plantation grown trees, and 360575 (152,118 in*lbf EI) to 341,855 psi (144,221 in*lbf EI) for the low and high log velocity groups, respectively. Strength results were similar for all groups with high standard deviations for both the naturally grown and the plantation grown trees. The low-velocity plantation group resulted in a parallel MOR of 7657 psi with an FbS of 8614 lbf*in; the high-velocity group resulted in a MOR of 8196 psi (9221 lbf*in FbS) with the middle group resulting in a MOR of 8444 psi and a FbS of 9500 lbf*in and standard deviations ranging from 1543 to 887 psi and 1736 psi to 997 lbf*in FbS for the low- and high-velocity groups, respectively. The low-velocity naturally grown trees showed a parallel MOR of 7535 psi with an FbS of 8477 lbf*in. The middle

Table 3. Summary of full panel bending test results.

| Velocity group | Avg. Para EI lb-in$^2$/ft | St. Dev. Para EI | Min. Para EI lb-in$^2$/ft | Max. Para EI lb-in$^2$/ft | Avg. Perp EI lb-in$^2$/ft | St. Dev Perp EI | Min. Perp EI lb-in$^2$/ft | Max. Perp EI lb-in$^2$/ft | *N* |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 468,460 | 27,506 | 423,683 | 507,755 | 200,382 | 14,131 | 181,587 | 228,351 | 10 |
| 2 | 519,123 | 29,340 | 476,882 | 570,536 | 191,164 | 8928 | 177,956 | 208,963 | 14 |
| 3 | 511,802 | 35,237 | 454,787 | 558,726 | 183,089 | 8276 | 169,557 | 193,269 | 12 |
| 4 | 437,345 | 38,018 | 353,406 | 476,419 | 177,304 | 11,185 | 161,751 | 197,359 | 14 |
| 5 | 531,667 | 30,269 | 491,763 | 577,644 | 196,799 | 11,096 | 180,342 | 207,987 | 8 |
| 6 | 519,738 | 59,678 | 400,182 | 596,165 | 180,973 | 13,099 | 160,865 | 206,298 | 12 |

Table 4. Summary of small sample test results.

| Velocity group | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Avg. Para MOE (psi) | 1,045,430 | 1,193,030 | 1,224,925 | 1,023,879 | 1,208,349 | 1,278,298 |
| Avg. Para MOR (psi) | 7657 | 8444 | 8196 | 7535 | 7734 | 8031 |
| Avg. Para FbS (lbf*in) | 8614 | 9500 | 9221 | 8477 | 8701 | 9035 |
| Avg. Perp MOE (psi) | 396,382 | 396,392 | 355,637 | 360,575 | 377,605 | 341,855 |
| Avg. Perp MOR (psi) | 3158 | 3261 | 3098 | 2936 | 3112 | 2936 |
| Avg. Perp FbS (lbf*in) | 3552 | 3668 | 3.485 | 3303 | 3501 | 3304 |
| Avg. Para % LE | 0.174 | 0.178 | 0.190 | 0.190 | 0.210 | 0.195 |
| Avg. Perp % LE | 0.352 | 0.351 | 0.368 | 0.375 | 0.438 | 0.400 |
| Avg. % Water Abs. | 17.3 | 17.9 | 18.5 | 17.8 | 20.9 | 18.9 |
| Avg. % Edge Swell | 10.7 | 11.5 | 11.5 | 11.3 | 12.4 | 12.0 |

LE, linear expansion.

log velocity group resulted in a MOR of 7734 psi (8477 lbf*in FbS) with the high-velocity group resulting in a MOR of 8031 psi (9035 lbf*in FbS) with similarly high standard deviations.

Dimensional stability was tested in the parallel and perpendicular strength axis using the LE wet/redry method of Voluntary Product Standard PS2-04 (2004). None of the samples in either machine direction were above the expansion limit of 0.5%. The parallel direction resulted in 0.174-0.190% expansion for the plantation groups and 0.190-0.195% for the natural growth groups (low- to high-velocity groups).

Water absorption and thickness swell were evaluated using the 24-h water soak/oven dry method in ASTM D 1037 (1999). Data for both properties were very similar for all groups and growth types.

Relationships were observed between the log velocity groups of plantation grown trees and full panel stiffness (EI) in both longitudinal and transverse directions, small sample bending stiffness parallel and perpendicular (MOE/EI), dimensional stability parallel and perpendicular (LE), and edge swell. For naturally grown trees, relationships were observed between the velocity groups and parallel full panel stiffness (EI), small sample bending stiffness parallel and perpendicular (MOE/EI), and perpendicular dimensional stability. Analysis of variance (ANOVA) was conducted to determine which velocity groups were significantly different for each of the tests that showed correlations with the log velocity groups. Analysis of parallel EI showed that the low-velocity plantation and natural groups performed poorly compared with the middle- and high-velocity groups (Fig 2). Perpendicular EI only showed a significant difference in the plantation grown trees with the high-velocity group performing poorly compared with the middle- and low-velocity groups (Fig 3).

ANOVA of small sample bending results showed the low-velocity groups for both growth types did not perform as well as the middle- and high-velocity groups for parallel stiffness, whereas the high-velocity groups did not perform as well in the perpendicular panel directions. Figures 4 and 5 show boxplots of the parallel and perpendicular results, respectively.

An ANOVA of dimensional stability showed the high-velocity group in the plantation growth type did not perform as well as the other velocity groups in the parallel and perpendicular directions (Figs 6 and 7). However, in the natural growth condition for perpendicular dimensional stability, the performance of each group was significantly different from each other, with the low-velocity group showing the best results, followed by the high- and middle-velocity groups.

No significant differences were seen in water absorption, but for the plantation grown trees the low stiffness group performed better than the middle- and high-velocity groups. No differences were seen in the naturally grown trees (Fig 8).

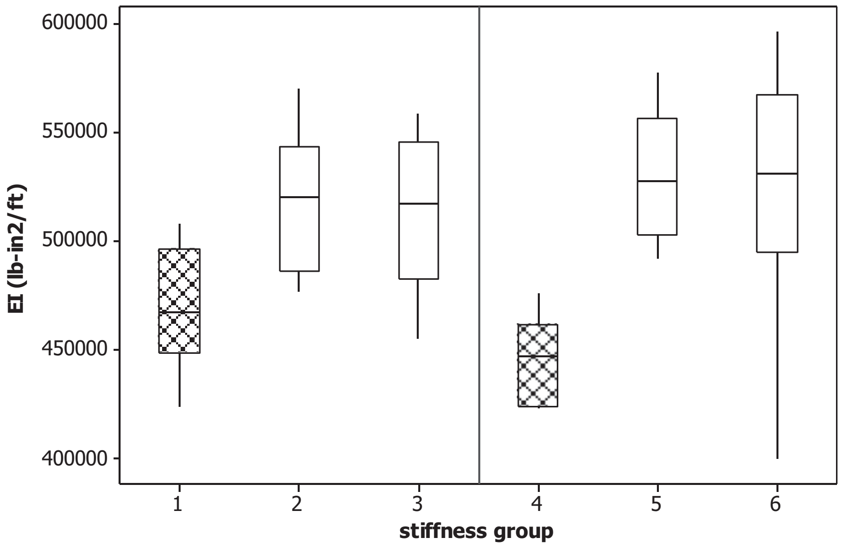



Figure 2. Plot of parallel full panel bending EI. Significant differences are denoted by the patterned boxes.

### DISCUSSION

Relationships were observed between log velocity (stiffness) groups and full panel stiffness, small sample bending stiffness, dimensional stability, and edge swell. Analysis showed that, in general, the low log velocity groups had poor full panel and small sample stiffness in the parallel machine direction with better dimensional stability and edge swell. The middle and high log velocity groups rarely performed differently from each other, while the low-velocity groups negatively influenced OSB panel stiffness. The high log velocity groups showed the poorest results in perpendicular panel stiffness and dimensional

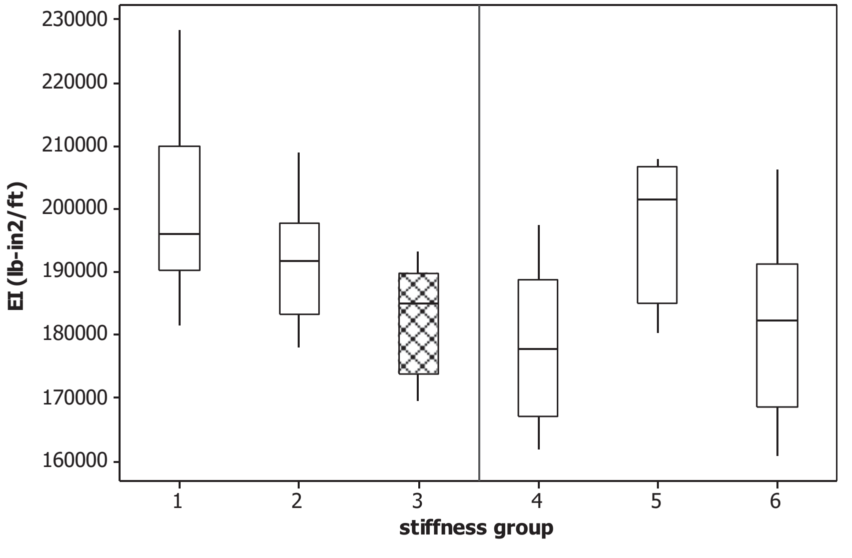



Figure 3. Plot of perpendicular full panel bending EI. Significant differences denoted by patterned boxes.

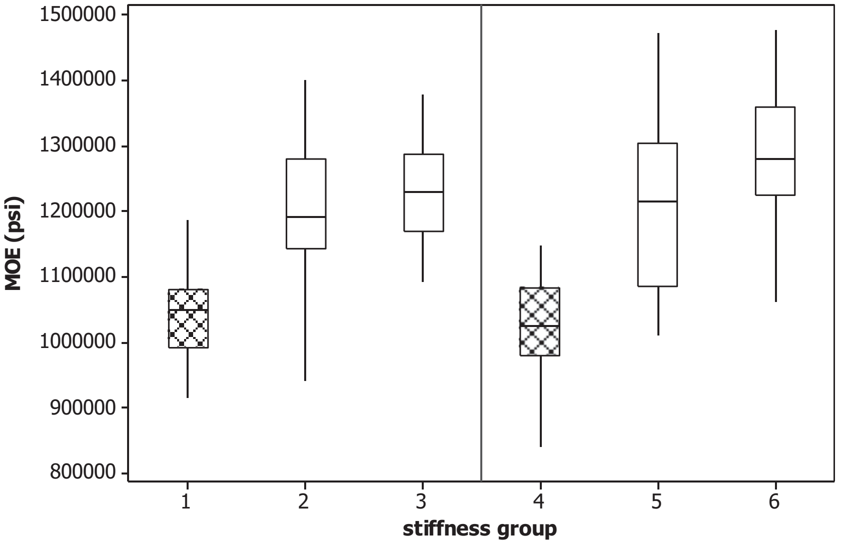



Figure 4. Plot of parallel small sample bending MOE. Significant differences denoted by patterned boxes.

stability. Typically, perpendicular panel properties are controlled more by manufacturing operations than by raw material quality, so poor performance along the perpendicular strength axis is not a concern for quality.

Plantation and naturally grown trees from the area sampled do not need to be segregated; log quality indicated no difference between growth types. The most important factor for segregation in the region analyzed was log velocity. The lowest velocity groups negatively impacted panel stiffness, which is the most important and the most difficult panel property to control by manipulating manufacturing parameters (Wu 1998; Wang and Winistorfer 2000). If low-velocity (stiffness) logs

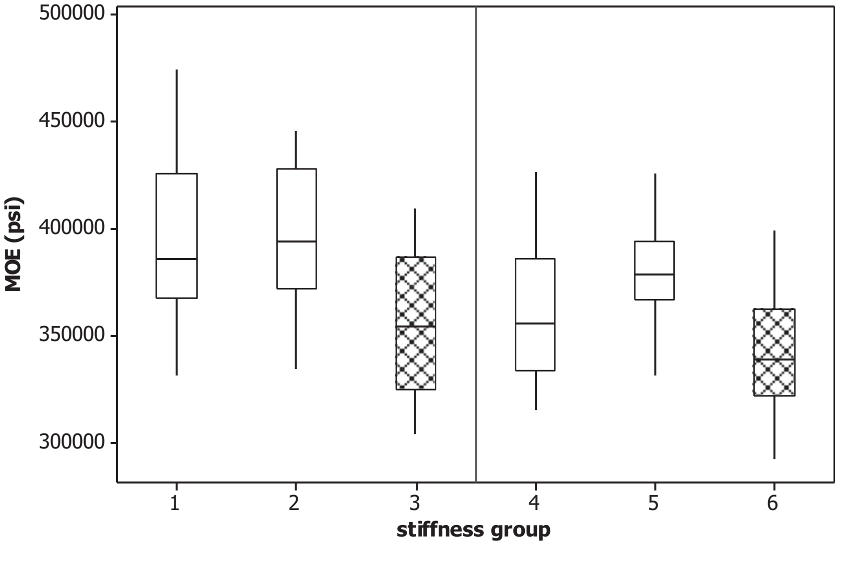



Figure 5. Plot of perpendicular small sample bending MOE. Significant differences denoted by patterned boxes.

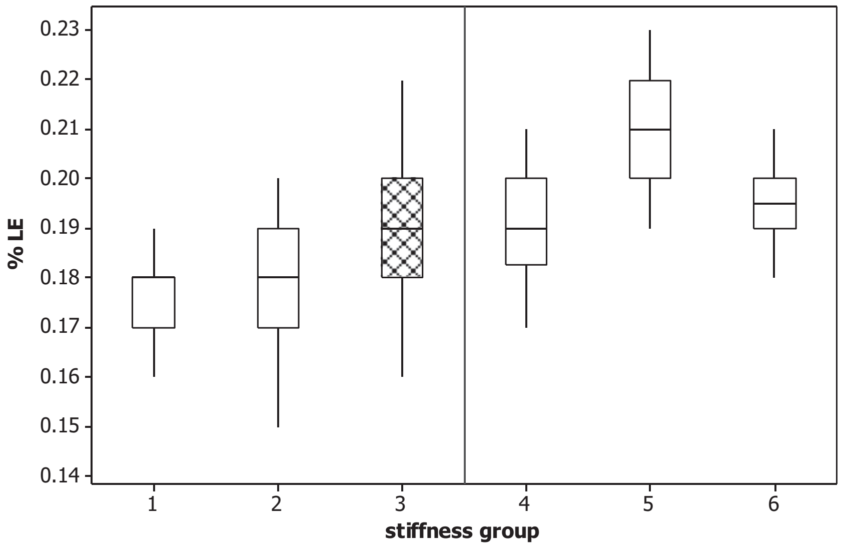



Figure 6. Plot of parallel linear expansion (%LE). Significant differences denoted by patterned boxes.

can be excluded before processing, panel stiffness should go up and ideally the amount of rejected material due to low quality would go down. Similar results have been seen in the lumber, plywood, and veneer industries using acoustic-based techniques (Carter and Lausberg 2001; Dickson et al 2005; Ross et al 2005; Moore et al 2013; Butler et al 2017; Simic et al 2019).

It was noted during processing that larger logs produced wider flakes due to the limitations of the laboratory flaker used. More of the lower stiffness material came from logs of larger diameter, which in turn had wider flakes. It was hoped that flake width would adjust itself by breakage of the flakes during the drying and blending processes, but the laboratory equipment was extremely gentle with

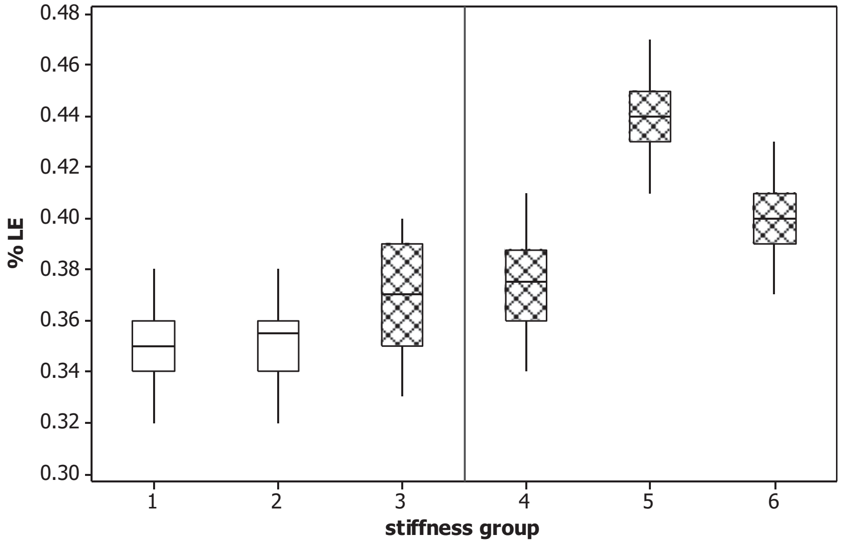



Figure 7. Plot of perpendicular linear expansion (%LE). Significant differences denoted by patterned boxes.

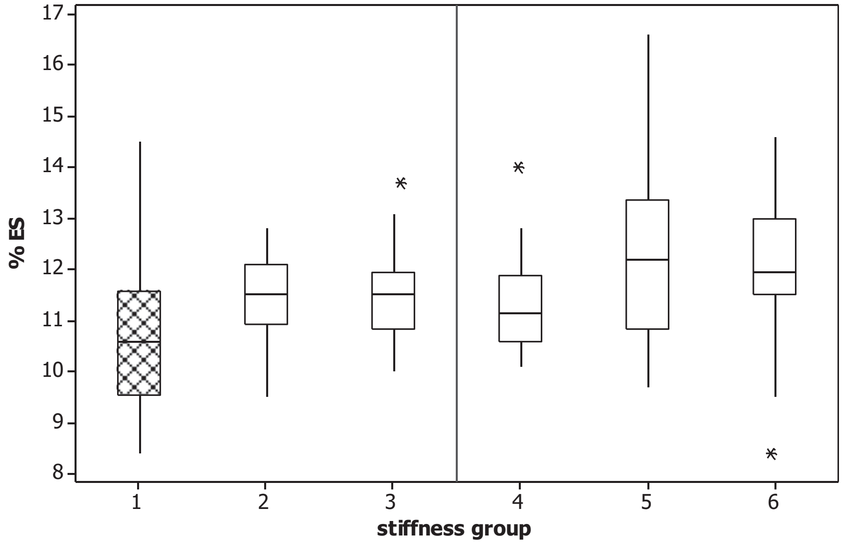



Figure 8. Plot of percent edge swell (%ES). Significant differences denoted by patterned boxes.

material (as the aim was to produce the best furnish possible), however, this is not true for manufacturing facilities. Perpendicular strength and stiffness as well as dimensional stability and water properties are significantly affected by wider flakes (Shuler and Kelly 1976; Wu 1998).

Low log velocity groups also showed significantly better dimensional stability and edge swell likely due to the wider flakes. In terms of this study, there was a lot of variation in the test results for edge swell and LE, so the difference detected might have been related to the relatively small sample size.

Overall, differences in log velocity (or stiffness calculated from velocity) had little or no effect on OSB panel properties other than stiffness, the single most important panel property. One explanation is that the logs were generally young and probably had a high proportion of juvenile wood which will lower OSB panel performance (Pugel et al 1990; Cloutier et al 2007). In general, acoustic velocity is an indicator of log quality. If low-velocity logs are segregated from the higher quality material, a stiffer panel should be made under normal operations. If producing a stiffer panel is not a problem for the manufacturing facility, using only higher velocity logs could result in the ability to lower panel densities, lower resin, and overall reduce raw material costs. If a plant does not make lower stiffness products, the purchase of low-velocity/stiffness material could be avoided by eliminating it at procurement sites. This approach would require some additional studies and would require the manufacturing facility to buy mostly procured logs, not gatewood, which is the current practice.

This study showed that log quality can affect OSB panel properties and that acoustic-based technology can be used to presort logs prior to processing to identify and remove low-velocity/stiffness logs from the high-velocity/stiffness material for high-strength structural panel production. However, the incorporation of acoustic tools into a manufacturing facility was not investigated. Important components to consider if acoustics were to be utilized for log segregation include the development of a sampling strategy and an examination of financial feasibility.

## CONCLUSIONS

Relationships were observed between log velocity (stiffness) groups and full panel stiffness as well as small sample stiffness. Analysis showed that, in general, the low log velocity groups had poor full panel and small sample stiffness in the parallel machine direction. The middle and high log velocity groups rarely performed differently, hence the low-velocity groups negatively influenced OSB panel stiffness. This indicates that by removing low-velocity logs from the material used to produce high-quality structural panels, a higher stiffness panel will be produced. This creates opportunities to lower panel densities and reduce resin usage, as well as reducing downgrade.

Relationships were also observed between log velocity groups and dimensional stability, internal bond, and edge swell. The low log velocity groups generally showed low internal bonding, better dimensional stability, and edge swell.

The high log velocity groups showed the poorest results in perpendicular panel stiffness and dimensional stability. Typically, these panel properties are controlled more by manufacturing operations than by raw material quality, so poor performance along the perpendicular strength axis is not a major concern for quality.

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**REFERENCES**

ASTM (1999) D1037: Standard test methods for evaluating properties of wood-base fiber and particle panel materials. ASTM, West Conshohocken, PA.

ASTM (2000a) D3043: Standard test methods for testing structural panels in flexure - Method C, pure moment test. ASTM, West Conshohocken, PA.

ASTM (2000b) D3043: Standard test methods for testing structural panels in flexure - Method D, flexure test for quality assurance. ASTM, West Conshohocken, PA.

Butler MA, Dahlen J, Eberhardt TL, Montes C, Antony F, Daniels RF (2017) Acoustic evaluation of loblolly pine tree- and lumber-length logs allows for segregation of lumber modulus of elasticity, not for modulus of rupture. Ann Sci 74:1-15.

Carter P, Lausberg M (2001) Application of Hitman® acoustic technology—The Carter Holt Harvey Experience. FIEA paper *in* Proc 4th Wood Quality Workshop: Tools & Technologies to Improve Log & Wood Products Segregation. Forest Industry Engineering Association, Rotorua, New Zealand, 29-30th October 2001.

Chauhan S, Donnelly R, Huang CL, Nakada R, Yafang Y, Walker J (2006) Wood quality: Multifaceted opportunities. Pages 159-202 *in* JC Walker, ed. Primary wood processing, principles and practice, 2nd edition. Springer, Dordrecht, The Netherlands.

Cloutier A, Ananias R, Ballerini A, Pecho R (2007) Effect of radiata pine juvenile wood on the physical and mechanical properties of oriented strandboard. Holz Roh Werkst 65:157-162.

Dickson R, Joe B, Harris P, Holtorf S, Wilkinson CA ( 2004) Acoustic segregation of Australian-grown *Pinus radiata* logs for structural board production. Aust For 67(4):261-266.

Dickson R, Joe B, Johnston D, Austin S, Ribton-Turner F (2005) Pre-processing prediction of wood quality in peeler logs and saw logs. Aust For 68(3):186-191.

Evans R (2006) Wood stiffness by X-ray diffractometry. Pages 138-146 *in* DD Stokke and LH Groom LH, eds. Characterization of the cellulosic cell wall. Blackwell Publishing, IA.

Forisk (2021) Top 10 North American Structural Panel Producers. https://forisk.com/blog/2021/03/23/top-10-north-american-structural-panel-producers/ (4 December 2021).

Grabianowski M, Manley B, Walker JCF (2006) Acoustic measurements on standing trees, logs and green lumber. Wood Sci Technol 40:205-216.

Huang CL (2000) Predicting lumber stiffness of standing trees. *In* Proc 12th International Nondestructive Testing and Evaluation of Wood Symposium, September 13-15, 2000, Sopron, Hungary.

Moore JR, Lyon AJ, Searles GJ, Lehneke SA, Ridley-Ellis DJ (2013) Within- and between-stand variation in selected properties of Sitka spruce sawn timber in the UK: Implications for segregation and grade recovery. Ann Sci 70:403-415.

Pugel AD, Price EW, Hse CY (1990) Composites from southern yellow pine juvenile wood. Part 1. Panel fabrication and initial properties. Forest Prod J 40(1):29-33.

Raymond CA, Joe B, Anderson DW, Watt DJE (2008) Effect of thinning on relationships between three measures of wood stiffness in *Pinus radiata*: Standing trees vs. logs vs. short clear specimens. Can J Res 38:2870-2879.

Ross R, Pellerin R (1988) NDE of wood-based composites with longitudinal stress waves. Forest Prod J 38(5):39-45.

Ross RJ, McDonald KA, Green DW, Schad KC (1997) Relationship between log and lumber modulus of elasticity. Forest Prod J 47(2):89-92.

Ross RJ, Willits SW, von Segen W, Black T, Brashaw BK, Pellerin RF (1999) A stress wave based approach to NDE of logs for assessing potential veneer quality. Part 1. Small-diameter ponderosa pine. Forest Prod J 49(11/12):60-62.

Ross R, Zerbe J, Wang X, Green D, Pellerin R (2005) Stress wave nondestructive evaluation of Douglas-fir peeler cores. Forest Prod J 55(3):90-94.

Schimleck LR, Evans R (2002) Estimation of wood stiffness of increment cores by near infrared spectroscopy: The development and application of calibrations based on selected cores. IAWA J 23(3):217-224.

Schimleck L, Apiolaza L, Dahlen J, Downes G, Emms G, Evans R, Moore J, Pâques L, Van den Bulcke J, Wang X (2019) Non-destructive evaluation techniques and what they tell us about wood property variation. Forests 10:728.

Shuler CE, Kelly RA (1976) Effect of flake geometry on mechanical properties of eastern spruce flake-type particleboard. Forest Prod J 26(6):24-31.

Simic K, Gendvilas V, O'Reilly C, Harte AM (2019) Predicting structural timber grade-determining properties using acoustic and density measurements on young Sitka spruce trees and logs. Holzforschung 73:139-149.

Voluntary Product Standard PS2-04 (2004) Performance standard for wood-based structural-use panels. https://www.nist.gov/system/files/documents/2017/06/13/ps2-04.pdf (4 December 2021).

Wang S, Winistorfer PM (2000) Fundamentals of vertical density profile formation in wood composites. Part II. Methodology of vertical density formation under dynamic conditions. Wood Fiber Sci 32(2):230-238.

Wang X, Ross RJ, Green DW, Englund K, Wolcott M (2002) Nondestructive evaluation for sorting red maple logs. *In* Proc 13th Int Sym on Nondestructive Testing of Wood, August 19-21, 2002, Berkeley, CA.

Wang X, Carter P, Ross RJ, Brashaw BK (2007) Acoustic assessment of wood quality of raw forest materials - a path to increased profitability. Forest Prod J 57:6-14.

Wang X, Verrill S, Lowell E, Ross RJ, Herian VL (2013) Acoustic sorting models for improved log segregation. Wood Fiber Sci 45(4):343-352.

Wu Q (1998) In-plane stability of oriented strandboard: Layer properties in relation to processing variables. Wood Fiber Sci 31(1):28-40.