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ORIGINAL ARTICLE

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Structural mechanics of wood composite materials II: Ultrasonic propagation mechanism and internal bonding of particleboard*

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Abstract Ultrasonic nondestructive evaluation (NDE) methods have been successfully applied for grading lumber and veneer at the in-plant level. To expand this application in wood composite production, further research is needed to elucidate the effect of differences of component elements within wood composite panels on the behavior of ultrasonic waves traveling through them. The objective of this study was to investigate the effects of the internal bonding of particleboard specimens containing component chips of different geometry on ultrasonic velocity. Commercial chips screened at four sizes were used to produce particleboard specimens with different internal bonding by controlling their out-of-press thickness at (a) a constant thickness for boards made of each chip size, and (b) four different thicknesses for boards made of the same chip size. Twenty-four boards were made with phenol-formaldehyde (PF) resin at 8% solid resin content in our laboratory. After the velocities of the waves traveling through the thickness of the boards were recorded, the internal bond strengths were tested. Results showed the density, internal bond state, and constituted chip geometry were the main factors influencing the velocity. NDE using ultrasonic waves is an available method to evaluate the internal bonding of particleboard with a density less than about 0.75 g/cm^3. With densities over that value, no significant changes of the velocity were found.

Key words Density · Internal bond · Chips geometry · Ultrasonic velocity

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Introduction

Ultrasonic technology, stress waves of high frequency, has been developed as a viable means to locate most defects in lumber. A typical application is to assess the properties of wood veneer in industrial systems, which encourages researchers to expand this technique for wood-based composite products. Substantial investigations have led to the design and test of longitudinal and transverse stress wave techniques for evaluating or predicting the physical and mechanical properties of wood-based composite boards.[1–5]

Most of these studies were based on propagating a stress wave through specimens in the longitudinal direction by a forced-vibration method, such as vibrating with a strike hammer. An excellent investigation utilizing this method has indicated that stress wave velocity and attenuation characteristics are related to the same mechanisms that control the mechanical properties of wood-based composite boards.[6] Considering the application in situ, the ultrasonic through-transmission method may be a better choice because measurements of ultrasonic parameters are more convenient and reliable.

With the ultrasonic through-transmission method, the influence of external noises from their site of origin and the receivable signals from these ultrasonic pulses propagating through the specimen can be neglected, and experimental accuracy can be improved only by improving the contact condition of the transducers with the specimen. Thus, good contact permits sufficient ultrasound energy propagation into and out of the specimen.

In comparison with the propagation of forced-vibration stress waves, ultrasonic through-transmission shows a greater attenuation of ultrasonic waves, because the attenuation increases exponentially with frequency. Weaker receivable signals of ultrasonic waves probably limit this application. However, measurements of the signals traveling through the thickness of wood composite boards might overcome this problem in that the transit distance of the wave is much shorter compared to measurements in the

Table 1. Chip sizes graded by geometry

Chip size	Length (mm)	Width (mm)
I	4.02 (1.68)	0.56 (0.23)
II	8.28 (3.54)	2.35 (0.37)
III	15.08 (4.13)	4.52 (0.26)
IV	18.76 (6.70)	6.56 (0.56)

Values in parentheses are the standard deviations

Table 2. Use of adhesive resin[a] and hot-pressing condition[b]

Pressure (MPa)	Time (min)
3	7
2	5
1	3

[a] Phenol-formaldehyde (8% resin content)
[b] Temperature was 150°C for all these conditions

Table 3. Target size of particleboard and use of various-size chips

Chip size	Thickness (mm)
II	26
II	21
II	18
II	12
I	16
II	16
III	16
IV	16

The lengths and widths of all boards were 400 mm and 400 mm, respectively

longitudinal direction, and as a result the attenuation loss is decreased. Moreover, because the ultrasonic wave can travel through the bonded points of the board, such measurements can be used to evaluate the internal bond (IB) of the board. Until now, there has been little information concerning interrelations between the internal structural characteristics of the board and ultrasonic velocities.

The objective of this study was to investigate the effects of internal bonding of particleboard specimens containing component chips of different geometry on the velocity of ultrasonic waves propagating through the specimens.

Materials and methods

Chip grade and board production methods

Commercial chips (mixed species of hard wood, with an average density of 0.4–0.5 g/cm^3) were sifted by size using a vibrating inclined screen. Four sizes (referred to as sizes I–IV in this report) of chips were graded by passing through a hand-held screen and were used for particleboard production. The length and width of 100 screened chips for each size were also measured by a micrometer caliper (Table 1). The screened chips were dried to about 3.5% moisture content (MC) and prepared to make particleboard.

For all boards, a constant weight of chips were sprayed with phenol-formaldehyde (PF) resin (PB1310; Oshika, Tokyo, Japan) containing 45% resin solids in a laboratory rotary drum blender for about 5 min. Mats were hand-formed in a 40-cm square frame. The MC of the chips in the mat before pressing ranged from 8.4% to 9.6%. To avoid blistering during the hot-pressing, a step-down press schedule was followed. The maximum pressure was 3 MPa, and total pressing time was 15 min (Table 2). The time interval from the application of resin to pressing was kept constant at 5 min in all trials to minimize any influence from the cure speed of the adhesive resin used.

Size II chips were selected to make particleboard specimens in four nominal thicknesses (Table 3). The chips for each size were also used to produce boards of uniform thickness (Table 3).

Three replicates were made for each board. Overall, a total of 24 boards were produced and kept at 65% relative humidity (RH) and 20°C for at least 2 weeks. Twelve 50-mm square samples were cut from each board for testing ultrasound propagation and IB strength.

Measurement of ultrasonic velocity and IB strength

Transit times of ultrasonic pulses were measured in perpendicular and parallel directions to the surface of each sample by a ultrasonic apparatus called Pundit (C.N.S. Electronic, London, UK) with 200-kHz transducers (4.37 cm^2 in cross area); the measurement was replicated three times at different positions on the surface of each sample, so the total contact area between the transducers and sample covered about 13.12 cm^2. The measuring accuracy was recorded precisely to 1% in microseconds. The velocity was then calculated by dividing the length the waves traveled by the transit time. The IB strength of the samples was measured according to procedures set forth in JIS A5908[7] standard.

Results and discussion

It has been well known that many factors, including internal structural differences and ambient conditions, affect the IB strength of wood-based composite boards. In this report, both chip and board production conditions and specifications were strictly controlled to investigate the effect of internal variable factors on the IB and ultrasonic velocity.

Effects of density and IB on velocity

As expected, the densities of the boards that contained size II chips increased with a decrease in the out-of-press thickness owing to the weight of the chips being kept constant (Fig. 1). In this case, all production conditions were assumed to be the same except the thickness for each board. As the compression ratio increased during the hot-pressing, heat from the steel platen was effectively transmitted to the center layer of the mat. Also, substantial voids between the

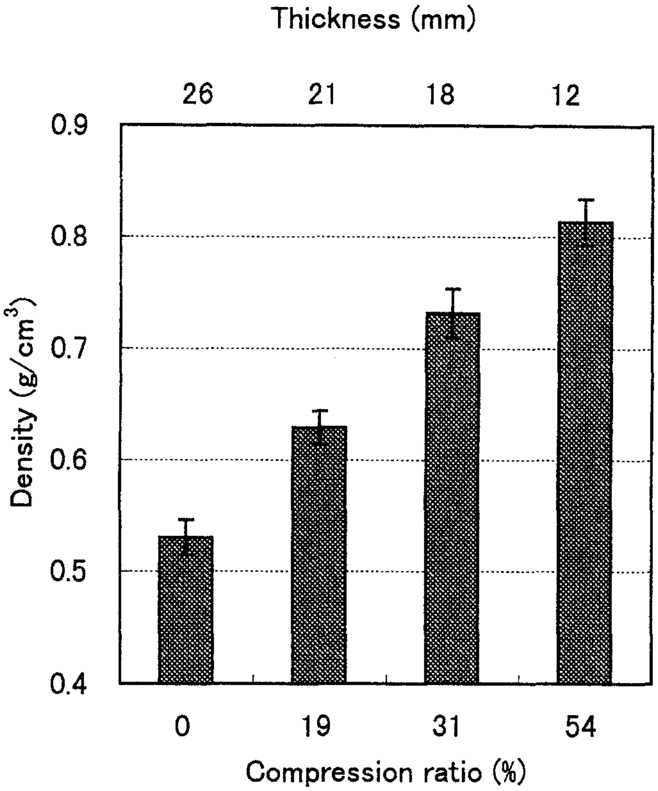

Fig. 1. Density dependence on the thickness of particleboard (PB) specimens that contained size II chips. Vertical bars indicate the standard deviation from 12 samples

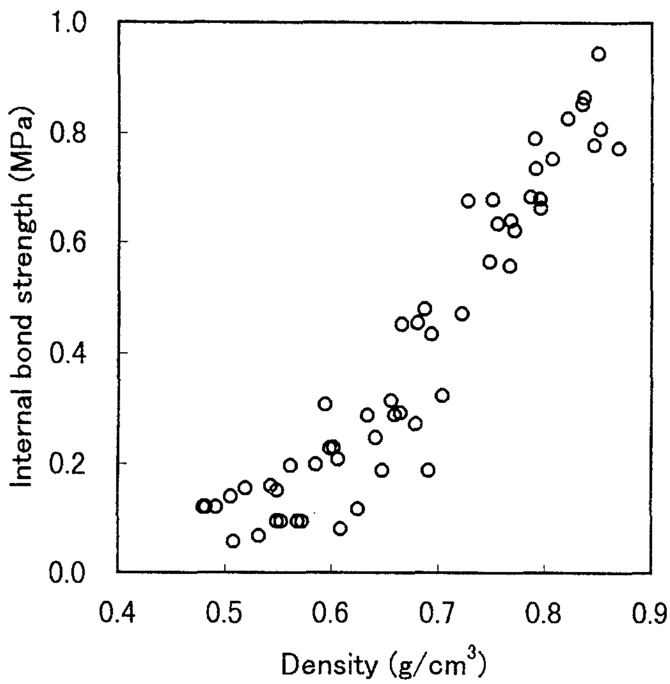

Fig. 2. Relation of internal bond (IB) strength and density for PB specimens that contained size II chips

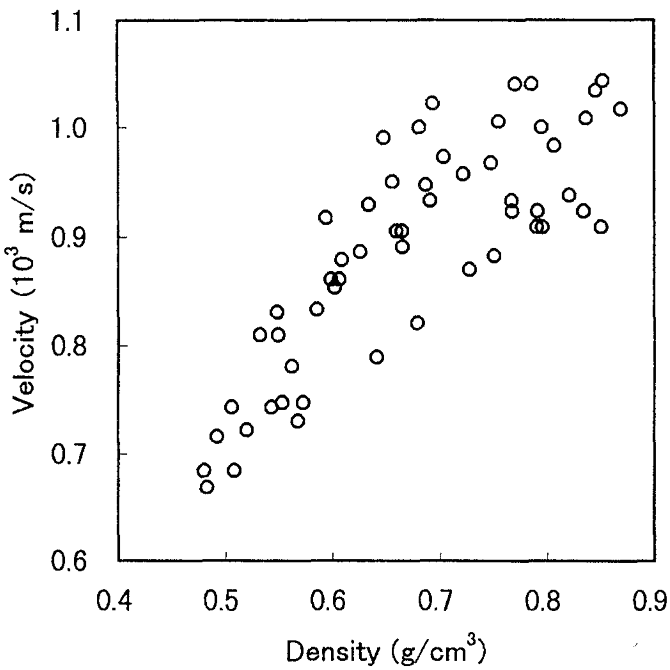

Fig. 3. Relation of ultrasonic velocity perpendicular to the board surface and density for PB specimens that contained size II chips

chips were decreased, and the interface of the chips was closed. All these factors improve the IB quality, such as through an increase in bonded points. The relations of density and IB strength are shown in Fig. 2.

It is well known that density is the primary factor influencing mechanical and physical properties of wood composite boards. Generally, high density in particleboard results in high IB strength properties, as it increases the number of bonded points. The high correlation between velocity and density was also recognized in this experiment. The velocity was positively correlated with the average density up to approximately $0.75\,g/cm^3$. However, when the density exceeded $0.75\,g/cm^3$ no obvious changes in velocity were observed except the value variables of the velocity becoming larger, as shown in Fig. 3. This phenomenon may be caused by the distributed uniformity of the component chips in the board due to the fact that the specimens were handformed. A plot of IB strength versus velocity also showed that a positive correlation existed between the IB and the velocity in the region below about 900 m/s. However, for high density boards over $0.75\,g/cm^3$, there was no correlation between IB strength and velocity in the thickness direction (Fig. 4). For boards less than $0.75\,g/cm^3$, IB was positively correlated with velocities measured in the thickness direction (Fig. 4). These results indicate that an increase in IB is reflective of a greater number of bonded points present with increasing density, as the velocity is affected by the wave-propagating pathway. In other words, the velocity was determined by the interactions of density and IB state. Thus, with increased density, substantial bonded points increase and the void areas decrease among the chips. Up to a point (about $0.75\,g/cm^3$ in this experiment), as density increases, the interface between the chips can be assumed to shorten the transit pathway for the ultrasonic waves, resulting in faster velocities. Above a density of $0.75\,g/cm^3$, there is no noticeable increase in velocity as the corresponding increase

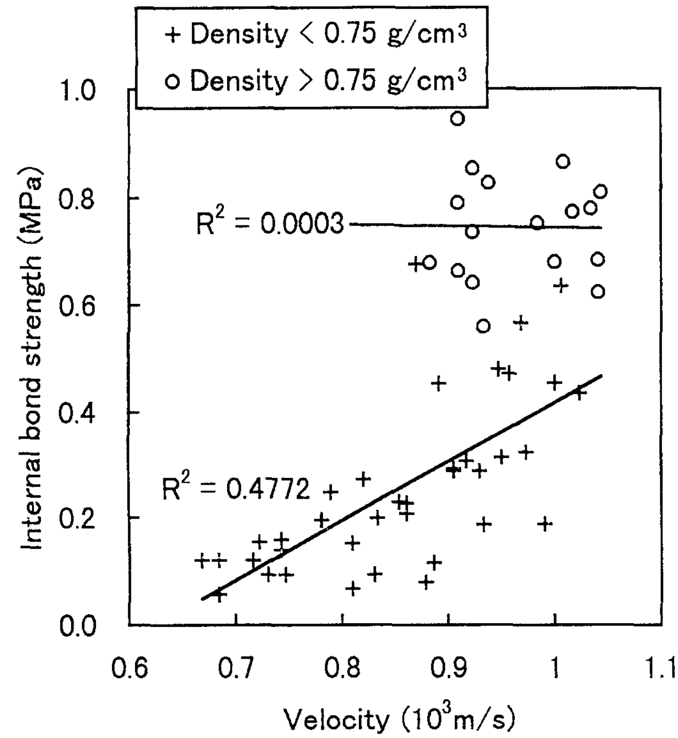

Fig. 4. Relation of ultrasonic velocity perpendicular to the board surface and IB strength for PB specimens of varying density

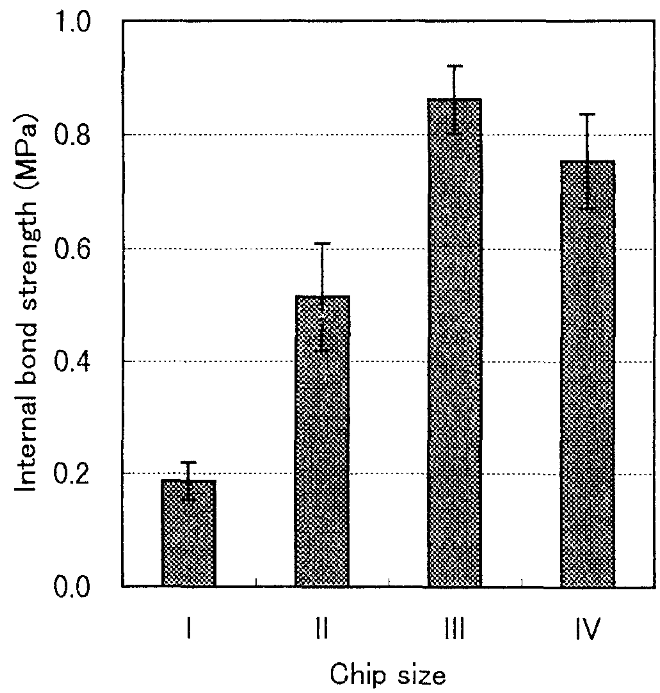

Fig. 5. Effect of chip geometry on IB strength for PB specimens at the same density. Each vertical indicates the standard deviation from 12 samples

in bonded points yield little increase in the effectiveness of the transit pathway. However, at higher densities (over 0.75 g/cm^3), the dominant orientation of the chips is in the plane of the board. In the transverse direction of chips, the internal compressed stress and plasticity deformation are elevated, especially for the chips near the surfaces, which can slow the ultrasonic velocities.[8] This suggests that using ultrasonic velocity may be of no or limited use when evaluating the IB of the boards at higher densities.

Effect of chip geometry on velocity

To elucidate the influence of chip size on velocity, boards of constant thickness and density but different chip size were made and tested. The boards had an average density of 0.71 g/cm^3 (standard deviation 0.05).

Figure 5 shows that different-geometry chips greatly influence the IB of the boards even if at equal densities. The highest IB values were obtained (0.86 MPa) for the board constructed with size III chips (the second largest chip size). Relatively lower values (0.75 MPa) were noted for the largest chips (size IV). In general, the IB strength values increase with enlarging chip thickness, particularly decreasing the length-to-thickness ratio.[9] However, neither extremely small nor extremely large chips yielded particleboard with high IB values.

Under the same applied resin content, small chips have an effectively large surface area, and therefore areas with insufficient or no resin were more prevalent. The use of large chips led to distributing the resin irregularly and unevenly, which also increased the surface area of chips on which the resin was poorly distributed during the hand-forming process.

The quantity and distribution of bonded points and voids among the chips can considerably change the pathway of the wave. This is due to the fact that the waves always propagate through a specimen traveling in the shortest pathway.[10] Consequently, these quantitative differences in bonded points and voids are supposed to be reflected in the velocity. As expected, the influence of chip geometry on velocity showed the same tendency as that on IB strength (Fig. 6). A regression analysis was performed to determine the correlation between IB and velocity (Fig. 7). It indicated that ultrasonic velocity could be utilized satisfactorily to assess the IB of the boards.

To investigate further the influences arising from the internal structural characteristics on wave propagation, the velocity in the longitudinal direction of the board was measured. Results (Fig. 8) indicated that different-geometry chips also influence the velocity in the longitudinal direction, and a positive relation was observed even for the boards containing size IV chips. For all the chip sizes, velocities increased with increasing chip size, suggesting that the velocity is predominantly determined by the chip size. Figure 8 also suggests that increased chip size reduces the uniformity of chip alignment, as suggested by the increased standard deviation. It also seems that the relative quantity of bonded points between the chips in the thickness direction does not dramatically influence the velocity when measured in the longitudinal direction.

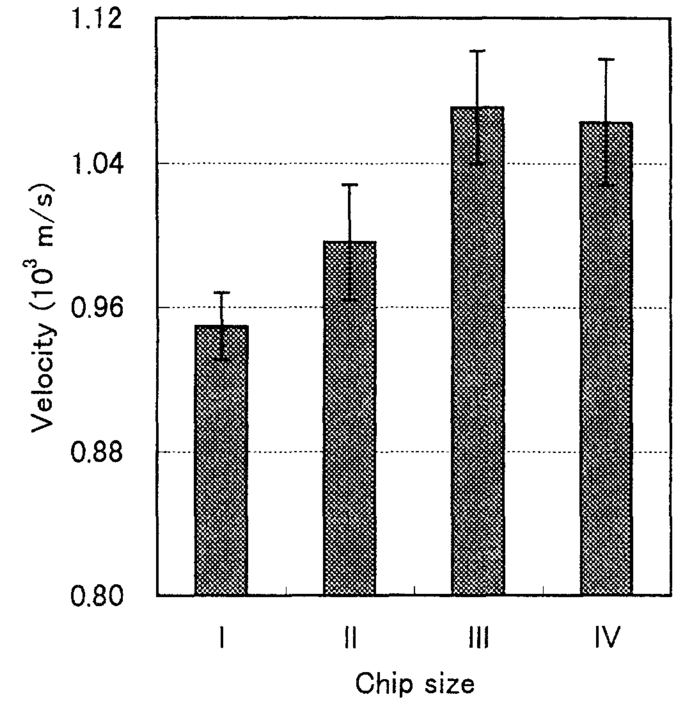

Fig. 6. Effect of chip geometry on ultrasonic velocity perpendicular to the board surface for PB specimens at the same density

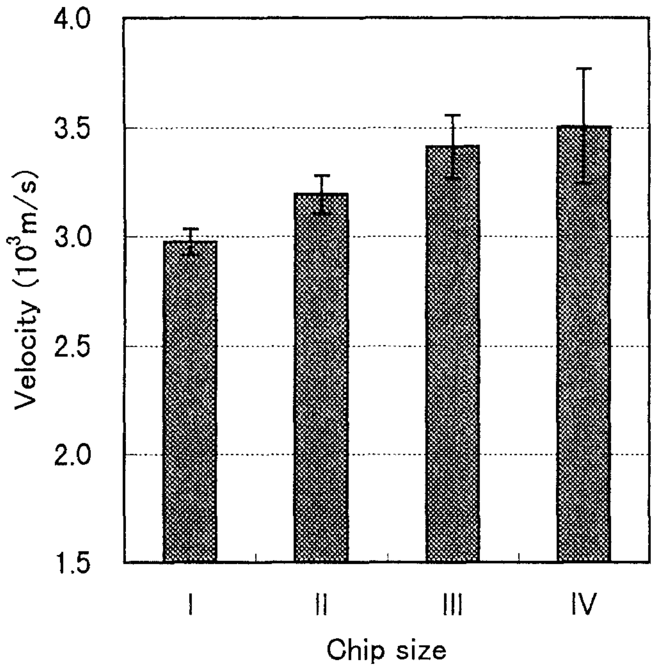

Fig. 8. Effect of chip geometry on ultrasonic velocity along the board surface for PB specimens at the same density

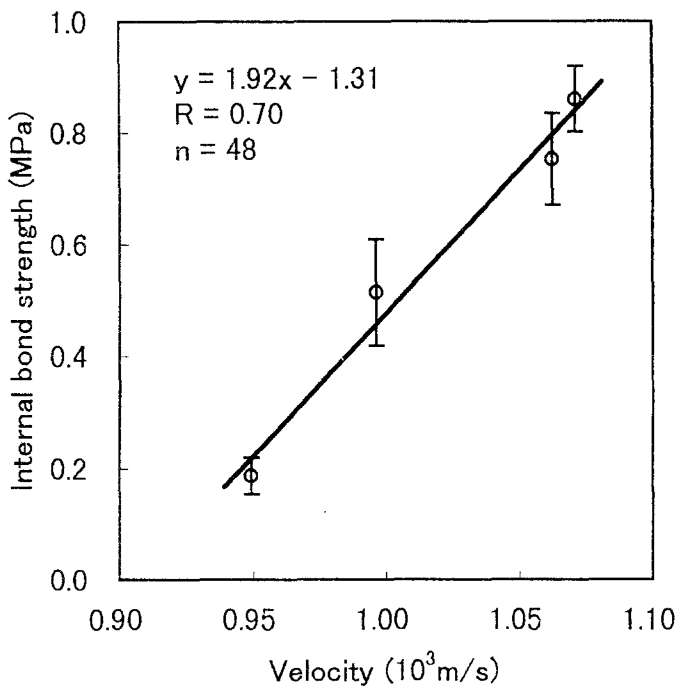

Fig. 7. Internal bond strength versus ultrasonic velocity perpendicular to the board surface for the same-density PB specimens containing different-geometry chips

Conclusion

Interrelations among density, IB state, component chip geometry, and ultrasonic velocity were investigated on laboratory-scale particleboards. Results indicate that not only density but also the IB state determine the velocity of ultrasonic waves. However, for the higher density boards (more than 0.75 g/cm^3), no significant change in velocity was found. Geometry and distribution of the chips are also significant factors influencing the IB and velocity. These results suggest that using ultrasonic wave techniques may provide a viable non-destructive method for evaluating the IB state of particleboards.

References

1. Kaiserlik JH, Pellerin RF (1976) Stress wave attenuation as an indicator of lumber strength. For Prod J 27(6):39–43
2. Gerhards CG (1982) Longitudinal stress waves for lumber stress grading: factors affecting applications: state of art. For Prod J 32(2):20–25
3. Bender DA, Burk AG, Taylor SE, Hooper JA (1990) Predicting localized MOE and tensile strength in solid and finger-jointed laminating lumber using longitudinal stress waves. For Prod J 40(3):45–47
4. Ross RJ, Pellerin RF (1991) Nondestructive testing for assessing wood members in structures: a review. General Technical Report FPL-70. USDA Forest Service, Forest Product Laboratory, Madison, WI
5. Pu JH, Tang RC (1997) Nondestructive evaluation of modulus of elasticity of southern pine LVL: effect of veneer grade and relative humidity. Wood Fiber Sci 29:249–363
6. Ross RJ, Pellerin RF (1988) NDE of wood-based composites with longitudinal stress waves. For Prod J 38(5):39–45
7. Japanese Standards Association (1994) JIS standard for particleboard JIS A 5908, Japan. Japanese Standards Association
8. Sasaki Y, Iwata T, Ando K (1998) Acoustoelastic effect of wood. II. Effect of compressive stress on the velocity of ultrasonic longi-

tudinal waves parallel to the transverses of the wood. J Wood Sci 44:21–27
9. Shuler CE, Kelly RA (1974) Effect of flake geometry on mechanical properties of eastern spruce flake-type particleboard. For Prod J 26(6):24–28
10. Armstrong JP, Patterson DW, Sneckenberger JE, Mallory JC, Pellerin RF (1991) Evaluation of a stress wave NDT technique for detecting skips in the gluelines of edge-glued red oak panels. For Prod J 41(11/12):61–66