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Article

Ultrasonic wave velocity as a universal metric for defect detection in timber structures: A case study on Japanese cedar wood (*Cryptomeria japonica*)

Chun-Won Kang[1], Masumi Hasegawa[2], Haradhan Kolya[1,*]

[1] Department of Housing Environmental Design and Research Institute of Human Ecology, College of Human Ecology, Jeonbuk National University, Jeonju 54896, Republic of Korea
[2] Faculty of Agriculture Department of Agro-Environmental Sciences, Kyushu University, Fukuoka 819-0395, Japan
*** Corresponding author:** Haradhan Kolya, hdk@jbnu.ac.kr

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Abstract: This study makes significant contributions to the field of ultrasonic testing (UT) by offering a novel approach to the identification of artificially introduced defects within Japanese cedar wood (*Cryptomeria japonica*). The findings are of particular relevance for the heritage conservation and construction sectors, where non-invasive defect detection is paramount. The study establishes a robust framework for assessing the structural integrity of timber by correlating ultrasonic wave velocity reductions with defect size and distribution. Big-sized defects led to more substantial decreases in wave velocity. The study establishes a robust framework for assessing the structural integrity of historical timber by correlating ultrasonic wave velocity reductions with defect size and distribution. This framework has the potential to be applicable to diverse wood species and defect types.

Keywords: ultrasonic wave velocity; wave propagation; wood defects; propagation time; Japanese cedar wood; non-destructive testing

1. Introduction

Wood is a versatile, renewable material critical in construction, furniture manufacturing, and various industrial applications [1]. Its unique combination of sustainability, mechanical strength, and aesthetic appeal has made it invaluable throughout human history. One of wood's most significant environmental benefits is its capacity to store carbon dioxide through photosynthesis, therefore helping to reduce global greenhouse gas emissions [2]. As nations attempt to use better building materials, wood's renewable nature and minimal environmental impact make it an appealing alternative for sustainable development [3]. Besides environmental benefits, wood has other advantages, including natural insulating capabilities that improve energy efficiency in buildings and a visual glow that adds to architectural aesthetics [4,5]. Despite these advantages, wood's mechanical performance can vary significantly due to species differences, growth conditions, and inherent structural variability [6–8]. Grain orientation, knots, and density changes complicate the assessment of wood's mechanical properties. This heterogeneity presents issues for the construction and timber sectors, where precise assessments of wood integrity are critical to ensuring the durability and safety of wooden buildings [9]. Defects introduced during growth or drying, such as cracks, splits, and resin pockets, can dramatically weaken the material, lowering load-bearing capacity and increasing susceptibility to failure under stress [9–11].

Wood is also extremely vulnerable to flaws induced by environmental and mechanical factors. Wind, insect infestations, and fungal decay can all cause internal structural damage, such as ring collapse or internal voids, even if no exterior degradation is obvious [12–14]. Drying pressures, a major concern in the manufacture of wood, can cause microcracks that are difficult to detect but have a significant impact on long-term durability [14]. These hidden defects offer significant risks in building applications, as unknown faults might result in catastrophic breakdowns over time. Furthermore, long-term exposure to moisture, temperature variations, and biological agents causes wood to decay, resulting in loss of strength, flexibility, and stress resistance [14–16]. This slow degradation emphasizes the importance of ongoing monitoring and maintenance to maintain structural dependability and safety.

To address these challenges, researchers have explored numerous nondestructive techniques (NDT) to assess wood integrity and welding defects in stainless steel sheets without compromising the material [17,18]. Techniques such as radiography [19], infrared thermography [20], and ultrasonic testing (UT) provide valuable insights into internal defects. Among these, ultrasonic testing has emerged as the most effective and widely adopted approach for evaluating the internal structure of wood. Different types of defects, including cracks, knots, and voids, produce unique ultrasonic wave behaviors, such as variations in velocity, attenuation, and echo patterns, which are critical for defect characterization [17,21]. Cracks and other discontinuities scatter and reflect waves differently from voids, producing distinct ultrasonic signatures that aid in NDT. UT offers fast, cost-effective, and highly sensitive detection of hidden defects by transmitting high-frequency sound waves through the material and analyzing the wave propagation characteristics [9,22]. It can detect small changes in wood density, identify internal defects such as knots and voids, and estimate mechanical properties like stiffness and the modulus of elasticity (MOE) [23–25]. This makes ultrasonic testing an effective tool for detecting wood degradation, evaluating timber, and forecasting long-term performance. The relationship between ultrasonic velocity and wood's MOE has been well established in several research studies, supporting the reliability of this technology for assessing mechanical properties [26–28]. This versatility has resulted in the widespread use of ultrasonic testing in the timber industry in countries such as South Korea, Japan, and Canada to evaluate structural wood in bridges, historical structures, and large-scale construction projects [29–33].

Despite the widespread acceptance of ultrasonic testing, there is a significant gap in the literature about the combined effects of defect size and frequency on ultrasonic wave velocity. While several studies have looked into the effects of single defects or material density on ultrasonic behavior, the interplay of many defects of differing sizes has received less attention [34–40]. This oversight is crucial because real-world timber often displays clusters of defects rather than individual abnormalities.

Previous studies, such as those by Bucur [41,42] and Mishiro [43], demonstrated that larger voids lead to greater ultrasonic attenuation, while smaller defects cause less disruption to wave propagation. However, these studies rarely address the cumulative effect of smaller defects distributed across the wood section.

Sandoz [44] highlighted that ultrasonic waves can bypass small voids, preserving transmission integrity, but larger, concentrated defects pose significant barriers to wave propagation. This interplay between defect size and distribution is vital for refining ultrasonic testing methods and enhancing accuracy in real-world applications.

The present study aims to bridge this gap by systematically analyzing the influence of artificial defects (holes) of varying diameters and quantities on ultrasonic wave velocity and amplitude in Japanese cedar wood (*Cryptomeria japonica*). By simulating realistic wood defects through controlled drilling, this study investigates how both defect size and frequency affect ultrasonic wave behavior. The results will provide new insights into the material's response to ultrasonic testing, contributing to the development of more refined defect detection models and improved wood classification techniques.

This research also aims to advance non-destructive testing techniques by offering a quantitative understanding of defect-induced wave attenuation. By establishing clear relationships between ultrasonic velocity, amplitude, and defect characteristics, this study can enhance existing predictive models and inform maintenance strategies for wooden structures in construction, heritage conservation, and timber grading industries.

2. Materials and methods

2.1. Sample preparation

To evaluate the effect of hole diameter and number on ultrasonic wave velocity, square beam specimens were prepared from air-dried Japanese cedar wood (*Cryptomeria japonica*). The specimens measured 22 × 22 × 400 mm (radial × tangential × longitudinal). Nine test specimens were used in total: three specimens were allocated to test the effect of the number of holes, while the remaining six were used to assess the impact of hole size on ultrasonic wave velocity.

For the hole size effect, the specimens were drilled with holes of varying diameters, ranging from 2 mm to 12 mm, positioned at the center of the beam and extending through the thickness. The following hole diameters were used: 2, 3, 4, 5, 6, 7, 8, 10, and 12 mm (**Figure 1a)**.

For the hole number effect, specimens were drilled with 1, 2, or 3 holes, each with a fixed diameter of 12 mm (**Figure 1b**). An additional group of specimens was drilled with 9 holes of varying diameters (2, 3, 4, 5 mm) and one square hole with a side length of 15 mm to investigate the combined effects of hole size and number (**Figure 1c**). The air-dried density of the wood was measured at 0.35 g/cm^3 (± 0.01). The selected hole diameters (2–12 mm) and numbers (1–3) were chosen to simulate practical wood defects that significantly affect structural integrity, such as those caused by decay or mechanical stress. Larger holes were selected to ensure measurable impacts on ultrasonic wave behavior and facilitate method calibration. However, drilling holes smaller than 2 mm presents technical challenges due to the unavailability of suitable drill bits.

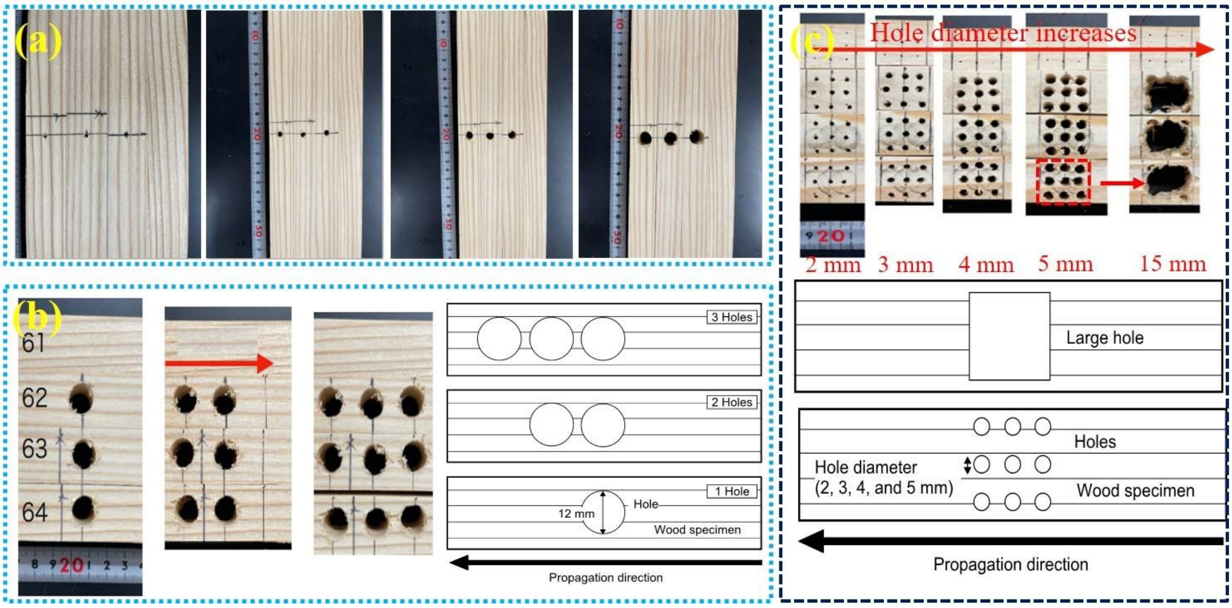

Figure 1. Photographs of test samples showing **(a)** variation in hole size; **(b)** variation in the number of holes; and **(c)** combined variation of hole size and number, used to study the effect on ultrasonic wave velocity.

2.2. Ultrasonic sound velocity and amplitude estimation

Ultrasonic wave velocity was measured using a pulser-receiver system (JPR-10CK, Japan Probe Co., Ltd.). A 200 kHz longitudinal ultrasonic wave (P-wave) was generated and transmitted through one end of the square beam specimen. Longitudinal waves propagate parallel to wave transmission direction and are highly sensitive to changes in material density, elasticity, and internal discontinuities, making them suitable for evaluating wood integrity. The airborne ultrasonic wave propagated longitudinally through the beam and was received at the opposite end by an ultrasonic wave receiver (JPR-10CN, Japan Probe Co., Ltd.). The signal was then amplified using a preamplifier (PR-60A, Japan Probe Co., Ltd.) and recorded in a personal computer for further analysis (**Figure 2a**,**b**). Each analysis was repeated 20 times, and the average values were used for the results and discussion.

The wave mode used in this study was non-dispersive longitudinal (P-wave) at 200 kHz, a frequency suitable for minimizing dispersion effects in solid wood. We measured the travel time to calculate the propagation velocity, ensuring that results primarily reflected the behavior of compressional waves without interference from mode conversion or reflected waves. Although shear waves (S-waves) and surface waves (Rayleigh waves) can also propagate in wood, longitudinal waves were selected due to their strong correlation with the modulus of elasticity (MOE) and their ability to penetrate deeply with minimal dispersion effects, ensuring stable and reliable velocity measurements.

The propagation time was determined by identifying the first zero crossing point of the received waveform (**Figure 2c**). The velocity of the ultrasonic wave was calculated using the following equation:

$$V = \frac{L}{T - T_0} \tag{1}$$

where V = propagation velocity (m/s), L = length of the sample (m), T = propagation time with the sample installed between the sensor (s), and T_0 = propagation time (s) without the sample installed.

To ensure consistent results, the environmental conditions during the experiment were controlled at a temperature of 21 ℃ and a relative humidity of 50%. Each test was repeated three times per specimen, and the averaged values were used for analysis. The amplitude of the ultrasonic wave was also measured to assess the effect of hole size and number on wave energy transmission. The amplitude represents the maximum voltage of the received waveform, which is influenced by the material's ability to transmit ultrasonic energy.

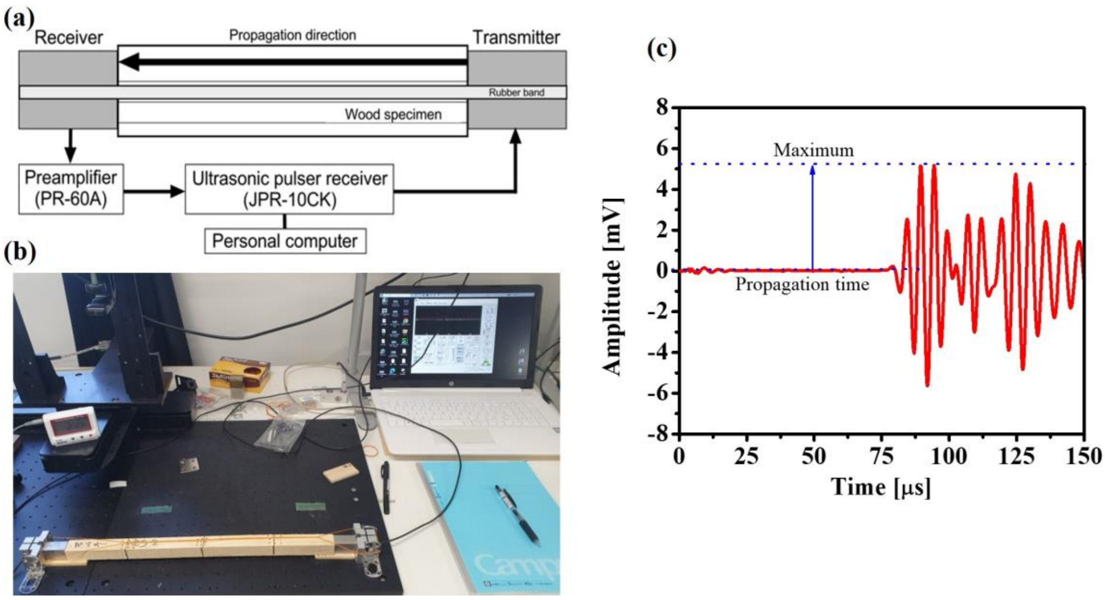

Figure 2. (a) Schematic diagram; **(b)** photograph of the ultrasonic wave velocity measuring apparatus; and **(c)** typical ultrasonic waveform.

3. Results and discussion

3.1. Ultrasonic sound velocity variation by hole size

The results presented in **Figure 3a** reveal a clear and consistent trend: As the diameter of the drilled holes increased from 2 mm to 12 mm, the ultrasonic wave propagation time steadily increased. The propagation time for the control sample (without any holes) measured approximately 85.804 µs. Propagation time increased progressively with larger hole diameters, reaching 86.064 µs for 12 mm holes. This increase in propagation time indicates that larger defects create significant disruptions in the ultrasonic wave's transmission path, forcing the wave to traverse around the holes, thereby extending the overall travel time. The greater the diameter of the hole, the more pronounced the deviation in wave travel. It suggests material discontinuity directly impacts wave behavior and slows its progression through the wood [41,45].

This observation aligns with established principles of wave mechanics in porous and heterogeneous materials [46,47]. Larger holes scatter and reflect ultrasonic waves due to the increase in their effective path length. The disruption occurs because ultrasonic waves preferentially travel through denser and continuous mediums [46,47]. However, more substantial sections of material are removed, and then the wave is forced to navigate around the hole's perimeter, increasing propagation time. This effect is compounded as hole diameter increases, reinforcing that defect size is critical in determining ultrasonic wave behavior in wood.

Figure 3b complements this analysis by demonstrating that ultrasonic propagation velocity decreases as hole diameter increases. The control specimen, characterized by a continuous wood matrix, exhibited an initial ultrasonic wave velocity of 5351 m/s. As holes of increasing diameter were introduced, this velocity gradually declined, falling to 5332 m/s for specimens with a 12 mm hole. This 0.30% reduction in wave velocity highlights the degree to which wave transmission efficiency diminishes with larger defects. The decline in velocity indicates the attenuation and scattering effects that result from material removal.

The reduction in ultrasonic velocity can be explained by the decrease in the cross-sectional area of solid wood. Larger holes reduce the amount of intact material available for the wave to propagate through, decreasing the wave's velocity as energy is absorbed, refracted, or scattered at the boundaries of the defect. This phenomenon exemplifies the more general idea that wave velocity in solid materials is inversely related to the degree of internal discontinuity or heterogeneity [41]. By creating greater holes in the wood's structure, they reduce the effective medium for wave propagation and increase attenuation effects.

Moreover, the cumulative nature of wave scattering and absorption with increasing hole diameter explains why larger holes result in more substantial velocity reductions. As the hole diameter increases, more material is removed, and the interface between the solid wood and the air-filled void becomes larger, creating additional opportunities for energy loss.

3.2. Ultrasonic wave velocity reduction vs. weight reduction

Figure 3c presents the relationship between the reduction in ultrasonic propagation velocity and the weight reduction percentage for wood specimens perforated with holes from 2 mm to 12 mm. The data were plotted using a linear regression model, resulting in a coefficient of determination (R^2 = 0.654), indicating a moderate positive correlation between the degree of weight reduction and the observed decrease in ultrasonic wave velocity.

The correlation shows that weight loss from wood significantly influences ultrasonic velocity, as the loss of structural mass alters the wood's ability to transmit acoustic waves efficiently. Larger or more numerous holes result in greater mass reduction, creating discontinuities in the material that disrupt wave propagation. These results are similar to the principles in ultrasonic testing, where wave velocity in solid materials is sensitive to density, porosity, and internal void changes. The positive relationship between weight reduction and velocity decline reinforces the understanding that material degradation can be detected through ultrasonic measurements, even at the microscopic level.

However, the R^2 = 0.654 value, while indicative of a moderate correlation, also suggests that additional factors influence wave velocity beyond simple material loss.

One key factor is the distribution of the holes within the specimen. Even if the total weight reduction is consistent across different samples, variations in the location and spacing of the holes can lead to differing impacts on wave propagation. For example, a single large hole located in the center of the wood may attenuate wave transmission more significantly than multiple smaller holes distributed across the surface. This suggests the concept of wave path disruption, where the placement of defects along the primary transmission route exerts a more substantial influence on velocity than defects located at the periphery.

Moreover, the shape of the perforations may contribute to variations in ultrasonic wave behavior. Circular holes create a uniform disruption to the wave path. However, square-shaped holes may introduce more complex scattering and reflection patterns. This may amplify energy dissipation and result in a steeper reduction in velocity than expected from weight loss alone.

3.3. Ultrasonic amplitude variation by hole size

Figure 3d shows the relationship between ultrasonic wave amplitude and hole diameter. It describes the insights into how defects influence wave energy as they propagate through the material. The graph reveals fluctuations in maximum amplitude as the hole increased from 2 mm to 12 mm. However, the changes were not statistically significant. It indicates that while larger holes introduce some degree of energy loss, the overall impact on amplitude remains relatively limited.

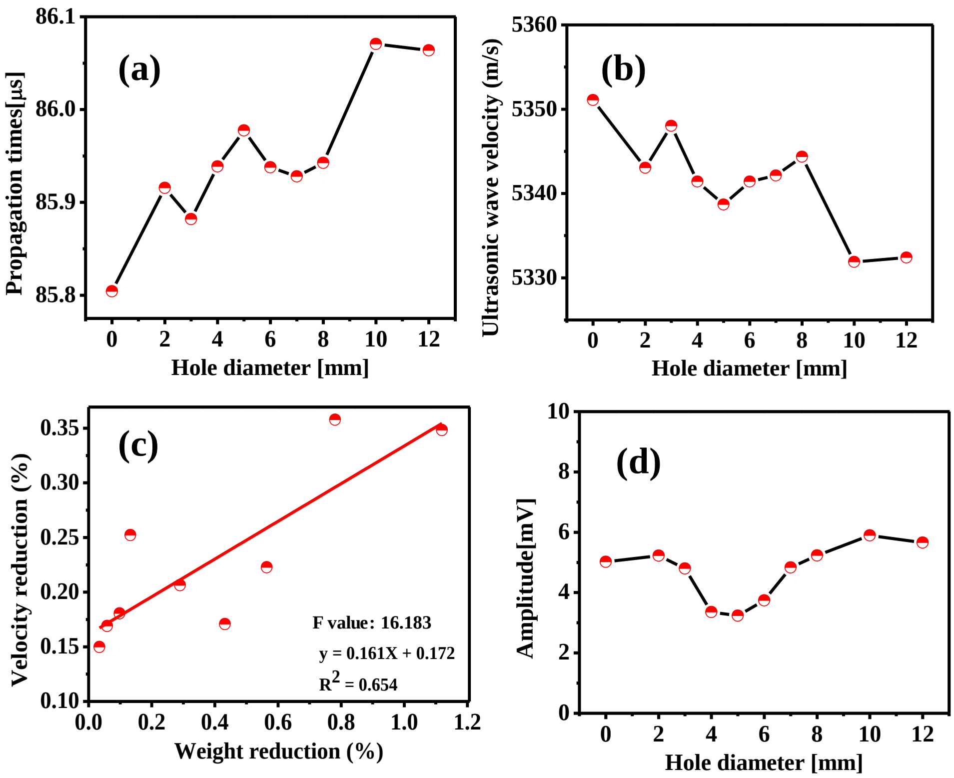

Figure 3. (a) Ultrasonic propagation time for varying hole sizes; **(b)** ultrasonic propagation velocity for varying hole sizes; **(c)** velocity reduction and weight loss (%) by perforation; and **(d)** maximum amplitude variation with hole size.

The data shows a slight decrease in amplitude as hole size increased, reflecting minor energy dissipation at the boundary of the perforations. However, this reduction was more or less comparable to the decrease in ultrasonic wave velocity. It shows that larger holes have a significant impact on structural integrity, but the wave's ability to absorb energy stays rather steady. This disparity demonstrates the many processes by which defects impact wave velocity and intensity.

The observed reduction in wave amplitude can be attributed to scattering and partial absorption of ultrasonic energy at the edges of the drilled holes [42]. The wave may encounter the boundary between solid wood and air-filled voids, and part of the wave is reflected, refracted, or absorbed, leading to a minor loss in amplitude. However, the amplitude's relative stability suggests that the ultrasonic wave can continue propagating through the material with minimal disruption to its overall energy, even as the hole size increases.

This contrasts with the behavior of ultrasonic wave velocity, which is more sensitive to discontinuities in the material. The velocity reductions observed in earlier figures indicate that the time required for the wave to pass through the specimen increases significantly as the hole size increases. This is because wave velocity is heavily influenced by the path length and density of the material, both altered by the introduction of holes. In contrast, amplitude reflects the amount of energy the wave retains as it propagates. Since smaller holes have less influence on the energy transfer process, their cumulative effect is reduced.

The minimal impact of hole size on amplitude can also be attributed to the fact that ultrasonic waves can bend around small obstacles (a phenomenon known as diffraction) [48]. As a result, smaller holes do not substantially block or reflect the wave, allowing much of the energy to pass through the surrounding material. This diffraction effect explains why amplitude remains relatively stable even as the hole diameter increases incrementally. Only when the hole size becomes sufficiently large, approaching the wavelength scale itself, does amplitude begin to show noticeable reductions. A summary of the results for ultrasonic wave amplitude and velocity is presented in **Table 1**.

Table 1. Summary of ultrasonic wave amplitude and wave velocity measurements for Japanese cedar wood specimens with varying hole diameters.

Hole diameter (mm)	Amplitude (mV)	Stdv.	Velocity (m/s)	Stdv.
0	5.02	2.92	5351.08	33.69
2	5.23	2.28	5343.05	30.67
3	4.80	1.87	5348.02	35.79
4	3.36	2.61	5341.41	31.49
5	3.23	1.80	5338.70	38.51
6	3.74	1.97	5341.42	26.69
7	4.83	3.12	5342.14	27.31
8	5.23	2.83	5344.36	25.63
10	5.89	3.72	5331.89	21.76
12	5.66	3.75	5332.40	24.31

3.4. Ultrasonic sound velocity variation by hole number

Figure 4a shows the variation in ultrasonic propagation time for specimens drilled with 1, 2, and 3 rows of holes, each consisting of 12 mm diameter perforations. As the number of hole rows increased, the propagation time slightly increased from 86.9 µs to 87.1 µs, suggesting increased internal disruption.

In **Figure 4b**, the ultrasonic wave velocity also showed a minor decrease as the number of holes increased. For holes (1–3 rows), the average propagation velocities were 5345 m/s, 5343 m/s, and 5332 m/s, respectively. The rate of change for three holes was 0.35% (**Figure 4c**), suggesting that while increasing the number of holes does slow the wave, the effect is not as significant as when increasing the hole diameter.

3.5. Amplitude variation by hole number

Figure 4d illustrates the variation in ultrasonic wave amplitude as the number of holes increased. Interestingly, the amplitude did not change as dramatically as the velocity did. Although the maximum amplitude increased slightly as the number of holes increased, these changes were inconsistent across different specimens. The overall wave energy remained relatively stable, suggesting that hole number has a lesser impact on wave energy compared to hole size. This could be due to the cumulative effect of multiple smaller disruptions (holes) causing less overall scattering than a single large perforation.

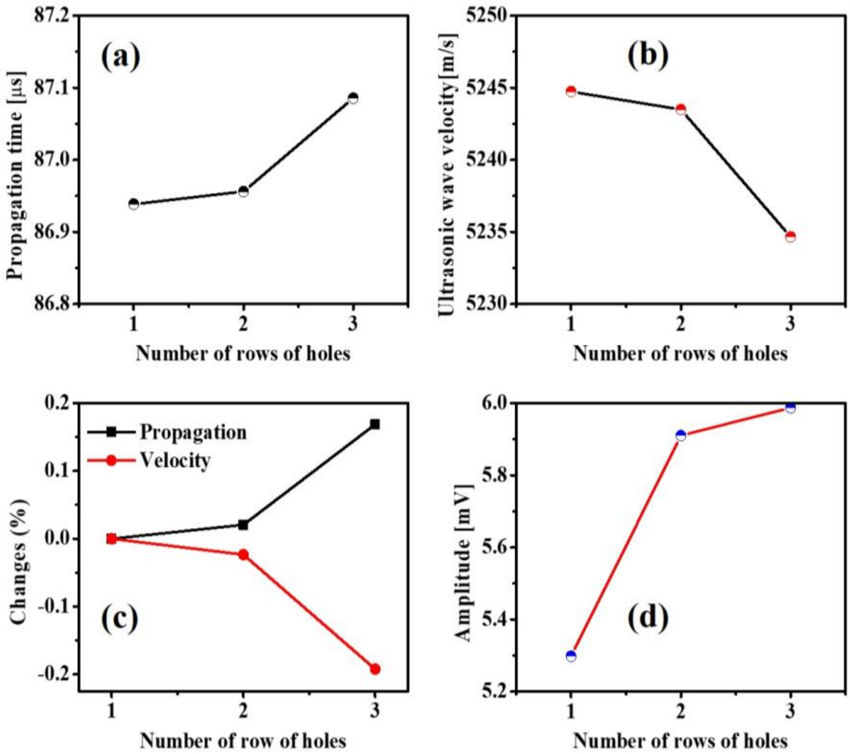

Figure 4. (a) Ultrasonic propagation time; **(b)** ultrasonic wave velocity; **(c)** percentage change in propagation time and velocity; and **(d)** maximum amplitude for specimens with 1, 2, and 3 rows of 12 mm diameter holes.

3.6. Combined effect of hole size and number

The combined effect of hole size and number on ultrasonic wave velocity was also analyzed. **Figure 5a** shows that the ultrasonic propagation time increased more substantially for larger holes and more complex shapes, such as square holes. When nine holes of 2 mm diameter were drilled into the specimens, the propagation time increased only slightly, from 97.4 µs to 98.6 µs. However, when the hole was a square with a side of 15 mm, the propagation time increased to 103.8 µs. This significant increase demonstrates that irregularly shaped holes and larger diameters cause greater disruption to the wave's transmission path.

Figure 5b presents the ultrasonic wave velocity variation for different hole sizes and numbers. For smaller holes (2 mm to 5 mm), the velocity reduction was minimal, but the introduction of a 15 mm square hole resulted in a velocity drop of approximately 350 m/s.

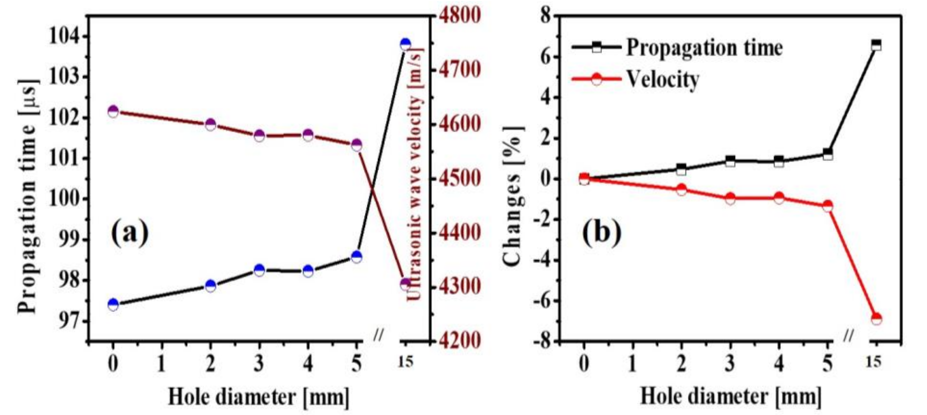

Figure 5. (a) Ultrasonic propagation time and velocity for control, 2 mm, 3 mm, 4 mm, 5 mm diameter holes, and a square hole with a side of 15 mm in perforated specimens; and **(b)** percentage change in propagation time and velocity.

3.7. Waveform and amplitude variation by hole size and number

Figure 6 illustrates the typical ultrasonic propagation waveforms for the control specimen and samples with hole diameters of 2 mm, 3 mm, 4 mm, and 5 mm and a square hole with a side of 15 mm. As seen from the figure, the waveform becomes progressively smaller as the hole diameter increases, with the largest reduction occurring for the square hole. This supports the observation that larger holes and irregular shapes scatter and absorb more wave energy, diminishing the amplitude and overall waveform strength. The smaller waveforms for larger holes indicate that perforations significantly disrupt the transmission of ultrasonic waves, leading to greater energy loss as the hole size increases. This behavior aligns with the findings on amplitude and velocity reduction.

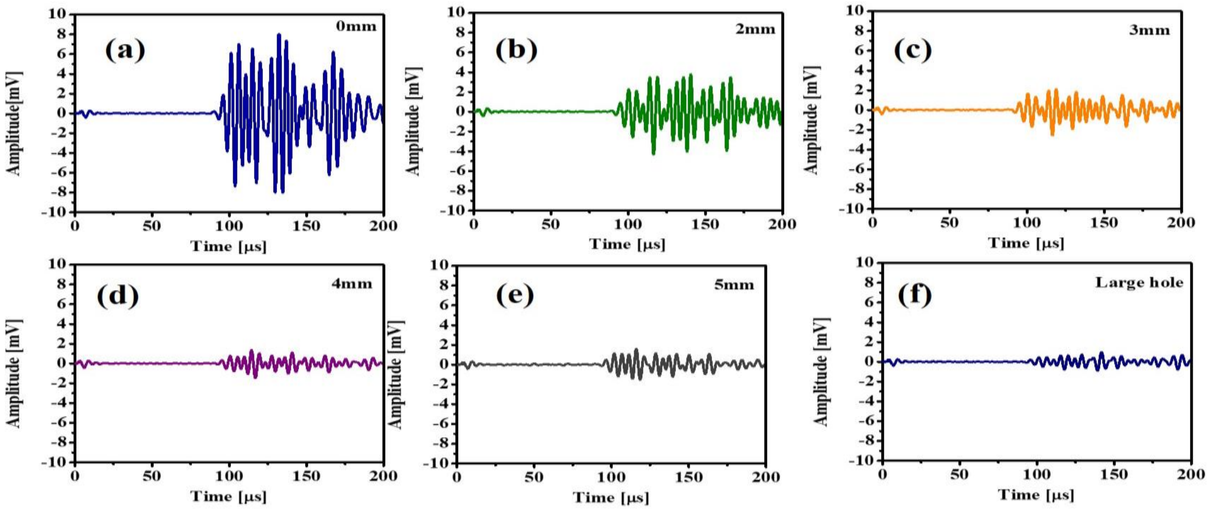

Figure 6. Typical ultrasonic propagation waveforms for control and specimens with **(a)** control; **(b)** 2 mm; **(c)** 3 mm; **(d)** 4 mm; **(e)** 5 mm diameter holes; and **(f)** a square hole with a side of 15 mm.

Figure 7a illustrates the relationship between the hole diameter and the maximum amplitude of the received ultrasonic waveform. As the hole diameter increased, the average maximum amplitude decreased significantly, from 5.4 mV to 1.0 mV. This reduction suggests that larger holes absorb or scatter more wave energy, resulting in a lower received signal. The rate of change in maximum amplitude increased as the hole diameter grew, with the amplitude decreasing by 82.3%. Even though the direction of the ultrasonic wave velocity and the orientation of the hole were orthogonal, the hole size had a clear impact on the maximum amplitude. Larger holes disrupt the wave's path more, reducing the energy that reaches the receiver.

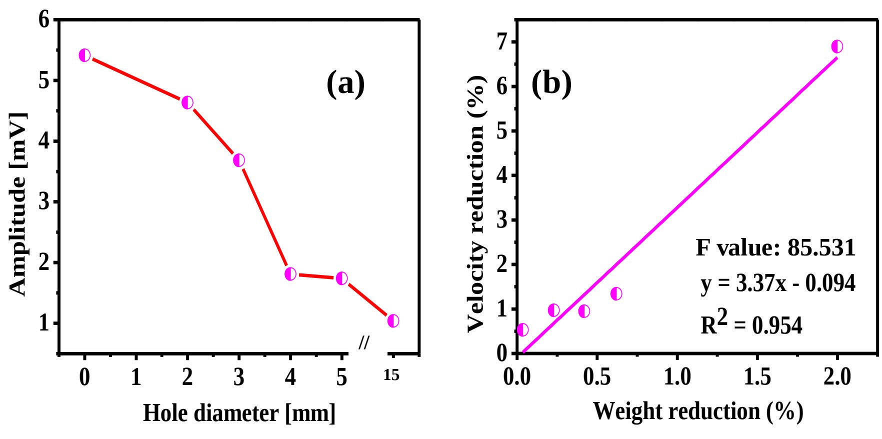

Figure 7. (a) Ultrasonic propagation waveform for control, 2 mm, 3 mm, 4 mm, 5 mm diameter holes, and a square hole with a side of 15 mm; **(b)** ultrasonic velocity reduction and weight loss rate for varying hole sizes and numbers.

3.8. Relationship between weight reduction and ultrasonic velocity

Figure 7b presents the relationship between the ultrasonic propagation velocity reduction ratio and the weight reduction rate for samples perforated with holes of 2 mm, 3 mm, 4 mm, and 5 mm diameters and a square hole with a side of 15 mm. The results show a strong positive linear relationship (R^2 = 0.954) between the weight reduction rate and the decrease in ultrasonic propagation velocity. This correlation suggests that the ultrasonic wave velocity decreases proportionally as the material is removed (leading to weight reduction) [49]. This correlation implies that ultrasonic velocity reduction can serve as a reliable indicator for predicting weight loss or material degradation in perforated wood samples. This finding is critical for non-destructive testing, as it allows for the prediction of material loss without physically damaging the wood.

4. Discussion

The results demonstrate that larger holes significantly reduce ultrasonic wave velocity and amplitude, underscoring their strong influence on the structural integrity of wood. This finding reinforces the usefulness of ultrasonic wave velocity as a non-invasive and reliable method for detecting internal defects. The observed reduction in wave velocity with increasing hole diameter is consistent with prior studies, which attribute such attenuation to wave scattering, reflection, and energy loss at defect boundaries [50].

A particularly noteworthy result is the strong correlation (R^2 = 0.954, F value 85.531, $p < 0.01$) between ultrasonic wave velocity reduction and weight loss. In contrast, **Figure 3c** showed a more moderate correlation (R^2 = 0.654, F value 16.183, $p < 0.01$). Future research should aim to include a broader range of defect types, such as natural cracks and knots, as well as numerical simulations, to develop a more comprehensive understanding of ultrasonic wave behavior in practical timber applications.

It is also important to recognize that many large defects, such as insect damage or branch hollows, can be detected visually during grading. However, ultrasonic testing becomes valuable in scenarios where internal or hidden defects are not visible, such as in preserved or painted structures, high-value heritage elements, or safety-critical applications. In these cases, ultrasonic evaluation can complement visual inspection and serve as a screening tool for deeper structural assessment.

Practical framework and implications: This study provides practical insights for applying ultrasonic testing in wood inspection. The results indicate that larger defects should be prioritized, as they have a more significant impact on wave velocity and amplitude. Additionally, the effects of clustered defects should be evaluated separately from those of single defects. Although artificial holes offered controlled experimental conditions, they may not fully capture the complexity of natural defects such as cracks or decay. Despite this limitation, the findings can contribute to field equipment calibration, the refinement of grading standards, and the integration of visual and ultrasonic inspection methods for more accurate assessment of wood integrity.

5. Conclusion

The findings demonstrate that ultrasonic wave velocity in Japanese cedar wood (*Cryptomeria japonica*) is more significantly affected by hole size than by the number of holes. When the hole diameter increased from 2 mm to 12 mm, there was an obvious reduction of ultrasonic wave velocity. This highlights the role of material discontinuity in attenuating wave transmission. In contrast, while increasing the number of smaller holes also led to velocity reductions, the effect was less pronounced, reaffirming that larger voids disrupt the wave path more severely.

Additionally, the study observed that ultrasonic wave amplitude decreased with increasing hole diameter and the number of holes. The reduction in amplitude indicates that substantial and frequent defects contribute to greater energy dissipation. It further supports the conclusion that larger perforations exacerbate acoustic degradation. However, the amplitude changes were not as significant as velocity reductions. It suggests that wave velocity is a more sensitive and reliable indicator of internal defects in wood. This distinction may be helpful for non-destructive testing applications to accurately identify structural defects.

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