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Assessment of Defect Severity in Wooden Pillars Using Ultrasonic Testing

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Abstract

Wooden structures are prone to internal defects, particularly cracks, which can significantly compromise their structural integrity over time. While ultrasonic testing is widely used, the relationship between ultrasonic wave behavior and crack severity is not well established. This study introduces a graded defect severity classification based on crack size and depth and evaluates its correlation with ultrasonic wave velocity, frequency, and attenuation in *Abies alba* (whitewood) pillars. Ultrasonic measurements were conducted on pillars with cracks of varying severity, including both defective (ranging from small to large cracks) and defect-free regions, using a digital oscilloscope and ultrasonic transducer system. Statistical analyses, including one-way ANOVA and Tukey HSD post-hoc tests, revealed significant differences in ultrasonic properties across severity classes. Among the parameters, wave velocity showed the greatest sensitivity to defect severity and correlated strongly with structural integrity, while frequency and attenuation provided supplementary but less distinct information. These findings confirm wave velocity as a reliable indicator of crack severity, and the proposed classification enhances ultrasonic data interpretation for more accurate assessment of structural degradation. This study advances the quantitative application of ultrasonic testing in timber evaluation, offering a refined approach to crack assessment in wooden pillars.

Keywords

defect severity, wave velocity, frequency, attenuation, non-destructive ultrasonic testing, wooden pillar

1 Introduction

Wood is widely used in construction due to its favorable mechanical properties, including a high strength-to-weight ratio, natural thermal insulation, and aesthetic appeal. However, it is also highly susceptible to defects such as cracks, knots, and biological decay resulting from environmental exposure, moisture changes, and mechanical stress [1–3]. These defects can compromise structural integrity over time, making early and accurate detection critical for ensuring the safety and longevity of wooden structures [4–6]. Traditional inspection methods, such as visual assessment and invasive mechanical testing, are often time-consuming, may cause material degradation, and are generally ineffective in identifying internal or hidden defects.

Non-destructive testing (NDT) techniques offer a reliable alternative by enabling internal evaluation without physically altering or damaging the material [7–9]. Among various NDT methods, ultrasonic testing has proven particularly effective for assessing the internal condition of wood. By analyzing wave propagation characteristics – specifically wave velocity, frequency, and attenuation, this technique enables the detection of structural irregularities while preserving the material's integrity [10–12]. Ultrasonic wave velocity provides critical insights into the mechanical properties of wood, such as elasticity and density, which are key parameters for assessing defect severity and overall structural integrity [13, 14], while frequency and attenuation characterize the wood's internal structure and facilitate the detection of potential defects [15, 16].

Despite the widespread application of ultrasonic testing in timber evaluation, the quantitative relationship between ultrasonic parameters and defect severity remains underexplored – particularly for cracks, which are among the most critical and commonly occurring structural flaws. Existing studies typically focus on general defect detection, without establishing objective classification schemes or examining how defect severity influences ultrasonic wave behavior.

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This study addresses this gap by introducing a graded classification system for crack severity based on measurable attributes – namely crack size and depth – and evaluating its correlation with ultrasonic wave velocity, frequency, and attenuation across both defective and defect-free regions in Abies alba (whitewood) pillars. This approach aims to improve the interpretability and reliability of ultrasonic data for non-destructive structural assessment.

The specific objectives of this study are to:

1. measure ultrasonic waveforms in wooden pillars with varying crack severity;
2. evaluate ultrasonic properties – wave velocity, frequency, and attenuation across defective and defect-free regions;
3. analyze the relationship between these ultrasonic parameters and a crack severity classification.

The findings are expected to enhance the quantitative capabilities of ultrasonic testing in timber evaluation and contribute to the development of more accurate, non-invasive methods for assessing the structural health of wooden components.

2 Materials and methods

This study investigates the relationship between ultrasonic parameters – specifically wave velocity, frequency, and attenuation – and crack severity classifications in *Abies alba* (whitewood) structural elements. The analysis differentiates between defect-free and defective regions, with defect severity categorized into distinct classes based on visible crack characteristics. To evaluate the sensitivity of each ultrasonic parameter to structural degradation, a comprehensive analytical framework was applied, incorporating one-way ANOVA, post-hoc Tukey HSD tests, effect size estimations (η^2 and Cohen's d), and visual data representations. This approach enabled a systematic assessment of how each parameter varies with increasing defect severity and facilitated the identification of the most sensitive indicators of internal damage.

Three cylindrical wooden pillars were selected as test specimens. All pillars were conditioned to a moisture content of 12% ± 1% and exhibited an average density of approximately 450 kg/m^3, representative of in-service conditions for indoor structural applications. The geometric characteristics of the specimens are detailed below:

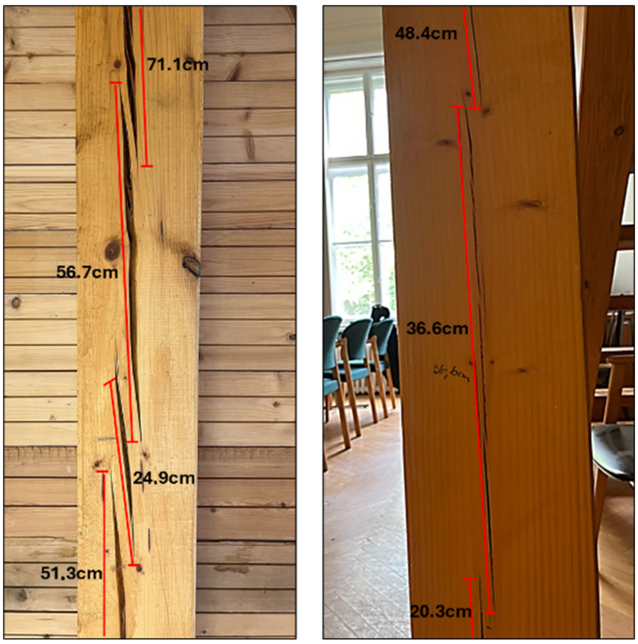
- Pillar 1: length 3.70 m; diameter 0.15 m;
- Pillar 2: length 2.10 m; diameter 0.10 m;
- Pillar 3: length 0.60 m; diameter 0.05 m.

The three pillars were selected to represent a variety of defect types, allowing for a focused analysis of ultrasonic properties across different defect severities. This approach, which prioritizes defect diversity over sample quantity, ensures that the study captures a range of defect scenarios, providing valuable insights into the relationship between ultrasonic properties and defect severity. These pillars, currently installed in an office environment, provide a representative sample set for assessing ultrasonic properties under realistic service conditions (20–23 °C, 45–55% RH).

Environmental factors such as temperature, humidity, and moisture content are known to influence ultrasonic wave propagation in wood. Increased moisture content typically elevates wave attenuation and reduces velocity, while temperature variations can alter wood stiffness, affecting wave speed and frequency response. Although ambient temperature and humidity were recorded during testing, they were not strictly controlled.

2.1 Specimen condition assessment and crack severity classification

Each pillar was inspected for visible surface defects. When cracks were present, their length and depth were measured using a high-precision digital caliper (accuracy ±0.01 mm). In cases where direct depth measurement was limited due to geometry, depth was inferred from surface morphology (Fig. 1).



(a) (b)

Fig. 1 Crack length measurements on wooden pillars: (a) distribution and extent of surface cracks on Wooden Pillar 1; (b) distribution and extent of surface cracks on Wooden Pillar 3

To ensure standardized evaluation across pillars, a four-tier crack severity classification system was developed based on the measured crack dimensions, in accordance with the National Grading Rule (NGR) for Dimension Lumber under ASTM D245-22 standard [17] (Table 1):

Each pillar was subdivided into multiple measurement zones covering both defective and defect-free regions to capture in intra-specimen variability in acoustic performance (Table 2).

2.2 Acoustic dynamic test of the pillar

The velocity (v) of sound propagating through the wooden pillars was measured using a FNIRSI 1014D digital oscilloscope (Shenzhen, China), with a bandwidth of 100 MHz and a sampling rate of 1 GSa/s. A FAKOPP-type ultrasonic sensor was securely affixed to the wooden surface using beeswax to ensure proper coupling (Fig. 2). Acoustic waves were generated by striking the pillar with a metallic hammer at predetermined locations.

Table 1 Crack severity classification according to ASTM D245-22 standard [17]

Severity class	Crack size	Description
Class 0	No visible crack	Defect-free zone
Class 1	< 2 cm in depth, shallow depth	Minor surface discontinuity
Class 2	2–5 cm in depth, moderate depth	Moderate structural crack
Class 3	> 5 cm in depth or deep penetration	Severe structural crack

Table 2 Crack severity classification and measured depth for *Abies alba* pillars

Pillar	Defect type	Location / size	Severity class	Measured depth
Pillar 1	Surface crack	Midsection (between: 71.1 cm – 56.7 cm – 24.9 cm – 51.3 cm) length	Class 3	~5.4 cm
	None	–	–	Not applicable
Pillar 2	Surface crack	Upper third, (between: 51.7 cm – 46.4 cm – 27 cm) length	Class 3	~5.02 cm
	None	–	–	Not applicable
Pillar 3	Surface crack	Lower third, (between: 48.4 cm – 36.6 cm – 20.3 cm) length	Class 1	~0.2 cm
	None	–	Class 0	Not applicable

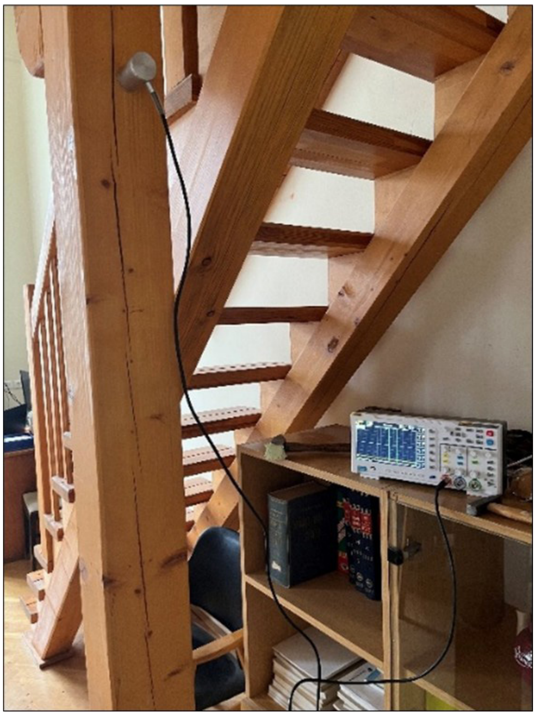


Fig. 2 Ultrasonic testing of the wooden pilar using FNIRSI 1014D digital oscilloscope

Measurements were conducted in the following positions:

- Edge / superior and inferior surfaces of the pillars;
- At 50 cm / superior, inferior, and lateral surfaces.

To ensure consistency and repeatability, each measurement was repeated three to five times at each location. The average of the repeated readings was taken as the representative value to reduce variability. The ultrasonic transducer was positioned at a fixed distance of 5 cm from the impact point on each surface, standardizing the signal path length across all tests. The experimental setup is illustrated in Fig. 1.

The wave velocity (v) was calculated using the standard time-of-flight formula (Eq. (1)):

$$v = l/t , \tag{1}$$

where v is the velocity (m/s) which calculated from the speed of sound travelling through the wood, l is the length of the pillar (m), and t is the time taken for the sound wave to travel from the transmitter to the receiver (s).

The FNIRSI 1014D oscilloscope was used to estimate the frequency of the acoustic signal. Since the device does not include an automatic frequency counter, the frequency was calculated manually from the waveform display. The time period (T) was determined by measuring the horizontal distance between successive waveform peaks using the oscilloscope's time/div grid (as shown in Fig. 3).

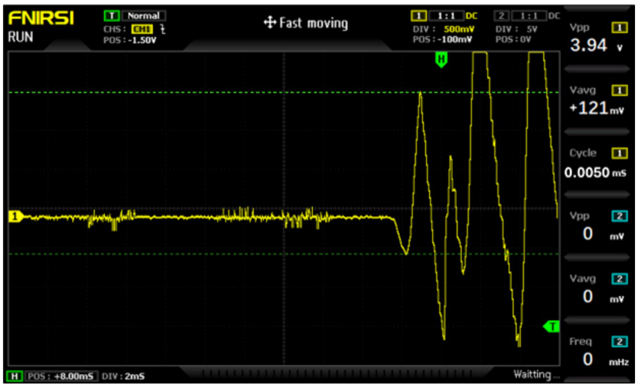


Fig. 3 Measurement of time period (T) using FNIRSI 1014D oscilloscope on wooden pillar (n = 1)

The oscilloscope was connected to an ultrasonic transducer positioned at one end of the wooden pillar.

To ensure accuracy, at least three complete waveform cycles were analyzed per measurement, and the average time period was used to compute the frequency.

The frequency (f) was subsequently calculated using Eq. (2):

$$f = 1/T, \tag{2}$$

where f is the Frequency of the wave (Hz), and T is the time period (s).

The attenuation coefficient (α) quantifies the rate at which the amplitude of an ultrasonic wave decreases per unit distance as it propagates through a wooden pillar. As the wave travels through the wood, its energy is absorbed by the material and scattered by internal structures, such as cracks. This results in a reduction of the wave's amplitude over distance.

Mathematically, this relationship is expressed in Eq. (3):

$$\alpha = \pi f / vQ, \tag{3}$$

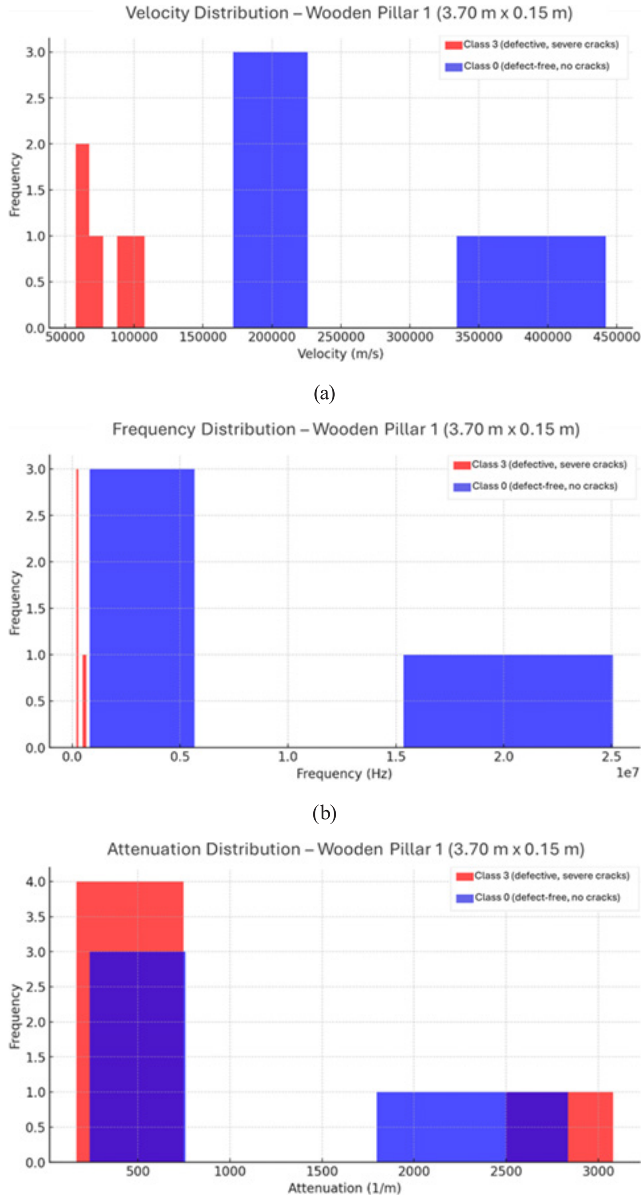
where α is the attenuation coefficient (1/m), v is the velocity of the wave through the wooden pillar (m/s), f is the frequency of the wave (Hz), and Q is the quality factor of wood (Q typically ranges between 20 and 50 for softwoods such as *Abies alba*) [18, 19].

3 Results and discussion

3.1 Ultrasonic properties in the wooden pillars

3.1.1 Wooden Pillar 1

Fig. 4 presents the ultrasonic property results for wave velocity (v), wave frequency (f), and wave attenuation (α) measured in both defective and defect-free regions of Wooden Pillar 1, with defect severity classified on a scale from 0 (defect-free) to 3 (severe defect). The results reveal distinct trends between the two regions, clearly



(c)

Fig. 4 Ultrasonic properties measured in Wooden Pillar 1 across varying crack severity levels (Class 0–3): (a) variation in ultrasonic wave velocity; (b) frequency distribution of ultrasonic signals; (c) attenuation of ultrasonic signal amplitude

highlighting the influence of defect severity on the material's ultrasonic properties.

The wave velocity in the Class 3 (defective region, severe cracks) ranges from 57,659.34 to 107,648.89 m/s, with a mean value of 62,968.47 ± 18,480.33 m/s. In contrast, the Class 0 (defect-free region, no cracks) exhibits a significantly higher wave velocity, ranging from 171,971.15 to 442,002.15 m/s, with an average value of 260,228.40 ± 96,021.40 m/s.

The wave velocity histogram further highlights this distinction, with Class 3 (severe cracks; defective zones) clustering in the lower velocity range, while Class 0 (no cracks; defect-free zones) displays a broader distribution concentrated in the higher velocity region. This clear separation underscores the influence of crack severity on wave velocity.

The substantial difference in wave velocity between these two regions indicates that defects significantly reduce the propagation speed of ultrasonic waves through the material. This observation aligns with the understanding that cracks disrupt the material's continuity, thereby reducing wave velocity. The reduction is attributable to displacement discontinuities at defect interfaces, which create stress concentrations that scatter waves and alter their propagation paths. As a result, mechanical integrity is compromised, and wave energy is either absorbed or scattered rather than transmitted effectively. These findings are consistent with previous studies [20–22].

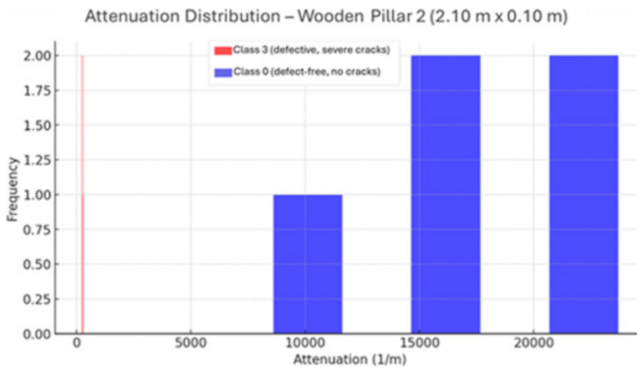
The frequency measurements reveal a similar trend. In Class 3 (defective region, severe cracks), the frequency ranges from 191,094.97 Hz to 663,570.01 Hz, with a mean of 569,000 Hz. In contrast, Class 0 (defect-free region, no cracks) show a broader range from 819,029.77 Hz to 25,064,513.23 Hz. The histogram further supports this observation, showing lower frequencies in defective regions due to scattering and wave disruption, which lead to energy loss. In contrast, defect-free regions display higher frequencies concentrated in the upper range with less attenuation, attributed to the absence of structural imperfections, as supported by El Masri et al. [23] and Wakata et al. [24]. As frequency increases, the likelihood of scattering due to defects also increases. This is because higher-frequency waves, with shorter wavelengths, are more susceptible to scattering by defects within the material. These findings are consistent with the work of Ohara et al. [25], and Gong et al. [26], who indicate that defects cause scattering and attenuation of higher frequencies, thereby narrowing the frequency spectrum.

Attenuation, which quantifies the loss of signal strength as ultrasonic waves propagate through a material, is significantly higher in defective regions compared to defect-free areas. In the Class 3 (defective region, severe cracks), attenuation values range from 165.71 to 3,080.96 1/m, with a mean of 677.84 ± 733.58 1/m. Conversely, Class 0 (defect-free region, no cracks) exhibits lower attenuation values, ranging from 238.12 to 2,835.13 1/m, with a mean of 35,710.26 ± 42,043.47 1/m.

The presence of defects disrupts the uniform propagation of ultrasonic waves, causing scattering in multiple directions, which leads to increased energy dissipation and consequently higher attenuation. Furthermore, defective regions are characterized by enhanced internal damping, where a portion of the ultrasonic wave energy is absorbed, either through localized heat generation or vibrational losses, thereby contributing to the elevated attenuation observed in these regions, as confirmed by Samaitis et al. [27] and Ono [28].

3.1.2 Wooden Pillar 2

Similar trends are observed in Fig. 5. In Class 3 (defective region, severe cracks), wave velocities range from 39,696.79



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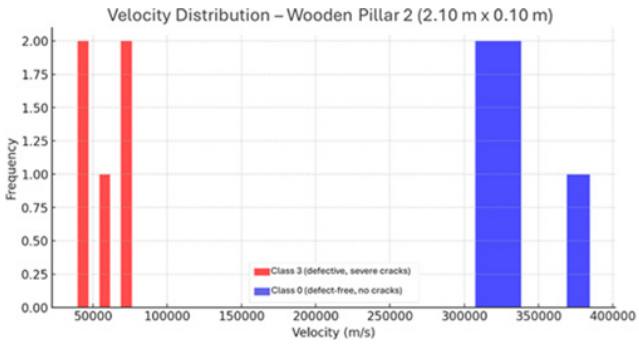

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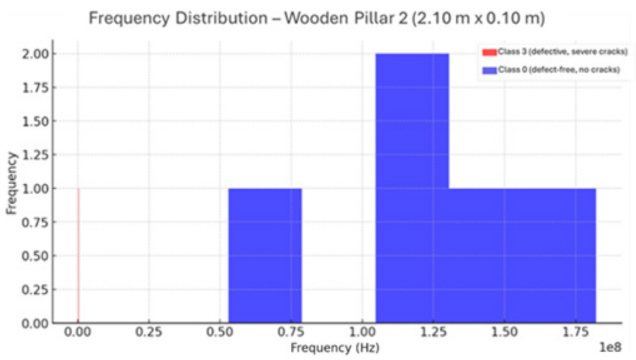

(c)

Fig. 5 Ultrasonic properties measured in Wooden Pillar 2 across varying crack severity levels (Class 0–3): (a) variation in ultrasonic wave velocity; (b) frequency distribution of ultrasonic signals; (c) attenuation of ultrasonic signal amplitude to 76,178.04 m/s (mean: 55,020 ± 14,692.14 m/s). This is significantly lower than the wave velocity in Class 0 (defect-free region, no cracks), which ranges from 307,512.08 to 384,474.55 m/s (mean: 318,400 ± 3,267.51 m/s) as confirmed by Subhani et al. [29] and Li et al. [30].

The frequency in the defective region Class 3 ranges from 232,450.02 to 356,760.61 Hz (mean: 320,832.62 ± 44,800.37 Hz), while Class 0 spans a wider range from 52,944,692.44 to 182,149,395.84 Hz, with a mean of 145,007,622.64 Hz.

Attenuation in the defective region (Class 3) ranges from 231.62 to 292.78 1/m (mean: 258.96 ± 27.67 1/m), compared to the defect-free region (Class 0), which exhibit higher attenuation values (8,607.48 to 23,688.09 1/m, mean = 16,392.86 ± 7,858.02 1/m). Consistently, the defective region exhibits lower wave velocities, higher attenuation, and a narrower frequency range, further emphasizing the detrimental impact of defects on the material's acoustic properties.

3.1.3 Wooden Pillar 3

The wave velocity in Class 1 (defective region, mild cracks) ranges from 49,954.21 to 54,308.47 m/s (mean = 51,420 ± 1,754.55 m/s), which remains significantly lower than that in Class 0 (defect-free region, no cracks), where the velocity ranges from 129,171.15 to 240,288.35 m/s (mean = 188,000 ± 26,092.61 m/s).

The frequency in Class 1 ranges from 1,014,713.34 to 1,053,518.75 Hz, whereas the Class 0 exhibits a much broader range from 293,341,924.49 to 497,549,418.48 Hz.

Attenuation in Class 1 ranges from 969.94 to 1,015.64 1/m (mean: 1,014.38 ± 13.29 1/m), while Class 0 shows a significantly higher attenuation range of 27,118.93 to 113,182.26 1/m, as shown in Fig. 6.

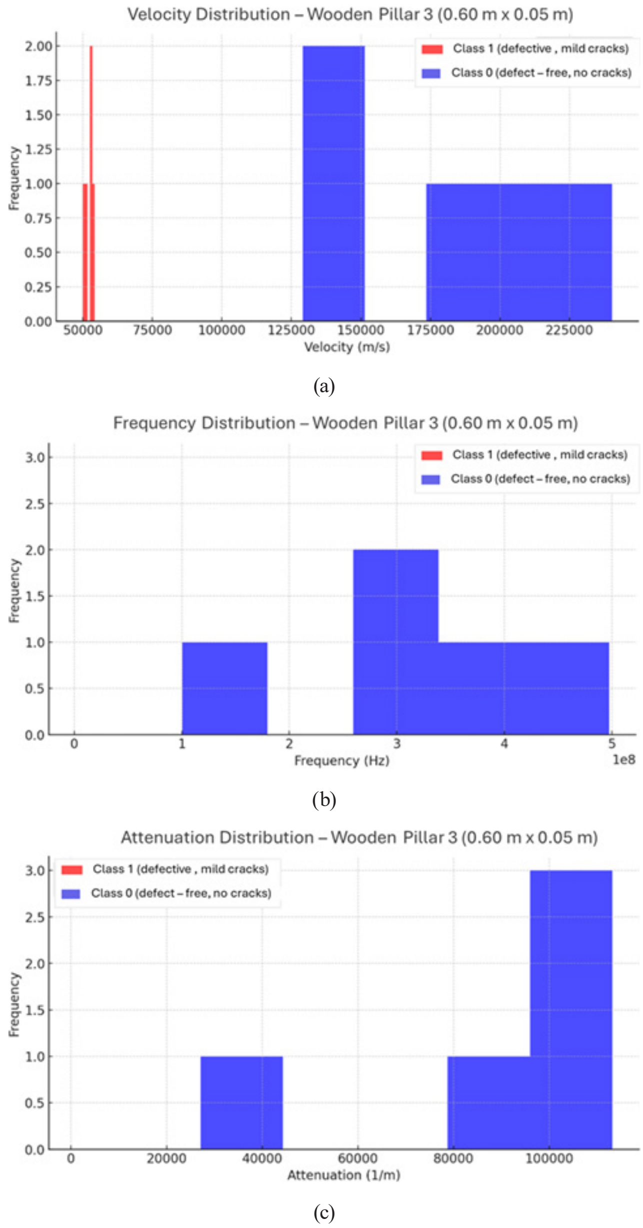

Fig. 6 Ultrasonic properties measured in Wooden Pillar 3 across varying crack severity levels (Class 0–1): (a) variation in ultrasonic wave velocity; (b) frequency distribution of ultrasonic signals; (c) attenuation of ultrasonic signal amplitude

3.2 Variations in ultrasonic properties and defect severity

To evaluate the relationship between defect severity and ultrasonic properties, all measurement points were assigned to a severity class ranging from 0 (defect-free) to 3 (severe defect), based on observable features such as crack size. A one-way ANOVA was conducted to examine variations across severity classes (Class 0–3) for three ultrasonic parameters: velocity, frequency, and attenuation. This analysis revealed statistically significant differences ($p < 0.05$) across all three parameters, confirming a clear relationship between defect severity and ultrasonic behavior (Table 3).

As shown in Table 3, the analysis of ultrasonic parameters (velocity, frequency, and attenuation) indicates statistically significant differences between the severity classes (Class 0–3), with p-values < 0.05. Among the three parameters, ultrasonic velocity (v) demonstrates the strongest differentiation across crack severity (p = 7.29E−6), followed by frequency (p = 0.00084) and attenuation (p = 0.0037). These results suggest that ultrasonic velocity is the most sensitive indicator of defect severity in wooden pillars.

To quantify the strength of these relationships, effect sizes (η^2) were calculated, indicating that defect severity

Table 3 ANOVA analysis of variations in ultrasonic properties across different crack severity classes (Class 0–3) in wooden pillars*

Test	Groups	DF	Mean sum of square (MSS)	F-value	p-value	Sig.
Velocity (v)		1	232584075000	30.14	7.29E−6	1
Frequency (Hz)	Crack severity (Class 0–3)	1	1.56E+17	13.97	0.00084	1
Attenuation (1/m)		1	9.41E+9	10.01	0.0037	1

* Abbreviations of Table 3: DF: degree of freedom; Sig.: significance at the 0.05 level; 1: significant; 0: not significant

explains a substantial portion of the variance in ultrasonic parameters. Velocity showed a large effect ($\eta^2 \approx 0.52$), while frequency ($\eta^2 \approx 0.33$) and attenuation ($\eta^2 \approx 0.26$) exhibited moderate effects.

In addition to the ANOVA results, 95% confidence intervals (CIs) for the mean differences between severity classes were computed to assess the precision of the observed effects. For ultrasonic velocity, the 95% CI for Class 0 (defect-free) ranged from approximately 250,000 to 290,000 m/s, whereas for Class 3 (severe defect), it ranged from approximately 58,000 to 68,000 m/s, indicating a substantial and well-defined reduction in wave velocity with increasing defect severity. The effect size, expressed as Cohen's d, was 2.5 for velocity, reflecting a very large magnitude of difference between these severity groups. Frequency also exhibited a significant decrease, with mean values declining from approximately 131 million Hz (95% CI ± 70 million) in Class 0 to 569,000 Hz (95% CI ± 203,000) in Class 3, corresponding to a large effect size ($d = 1.1$). Attenuation demonstrated a moderate effect size ($d = 0.93$), with mean attenuation values increasing from 707 1/m (95% CI ± 236) in Class 0 to 34,689 1/m (95% CI ± 21,133) in Class 3.

These differences reflect the varying sensitivities of ultrasonic parameters to structural defects. Velocity is highly sensitive to changes in stiffness and density caused by cracks that disrupt wood fiber continuity [31, 32], making it a robust indicator of defect severity. Frequency captures alterations in wave energy distribution due to scattering from internal irregularities, which broaden the frequency spectrum and lower the dominant frequency, resulting in greater variability and reduced sensitivity [33–35]. Attenuation, primarily influenced by absorption and scattering from microfractures and small-scale defects, increases with defect severity due to enhanced energy loss; this effect is amplified at higher ultrasonic frequencies as shorter wavelengths interact more intensely with fine-scale irregularities (see Fig. 7), consistent with previous studies [36–38]. Attenuation's responsiveness to minor defects and sensitivity to measurement conditions contribute to its comparatively smaller effect size.

To further clarify which specific pairs of severity classes contributed to the observed differences, a Tukey's Honestly Significant Difference (HSD) post-hoc test was conducted. The results are summarized in Table 4.

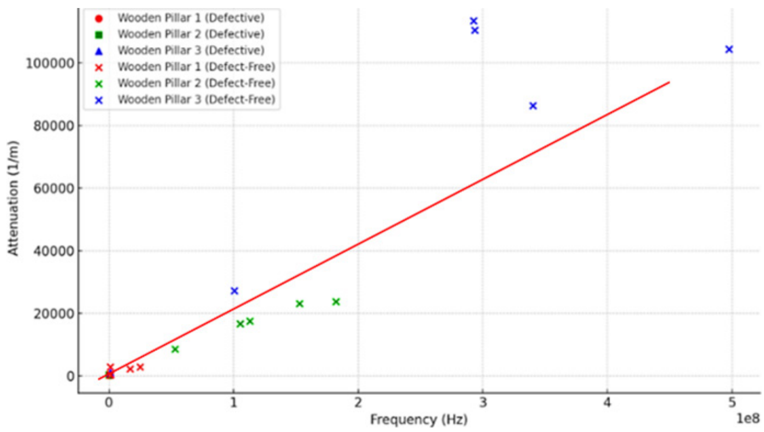

Fig. 7 Relationship between frequency and attenuation in wooden pillars with varying crack severity (Class 0–3)

Table 4 Post-hoc Tukey HSD test results for pairwise comparisons of ultrasonic parameters across defect severity classes (Class 0–3) (significant differences ($p < 0.05$))

Ultrasonic parameter	Class 0 vs. Class 1	Class 0 vs. Class 3	Class 1 vs. Class 3	ANOVA p-value
Velocity (m/s)	($p < 0.01$) significant	($p < 0.001$) significant	($p < 0.05$) significant	2.86×10^{-7}
Frequency (Hz)	($p = 0.094$) non-significant	($p = 0.0021$) significant	($p = 0.128$) non-significant	0.0042
Attenuation (1/m)	($p = 0.219$) non-significant	($p = 0.0118$) significant	($p = 0.186$) non-significant	0.0179

The Tukey HSD analysis revealed that:

- Velocity showed statistically significant differences across all pairwise comparisons. This confirms that ultrasonic velocity is a sensitive and reliable indicator of structural degradation across both mild and severe defect levels, capable of detecting even subtle changes in internal integrity.
- Frequency displayed a significant difference only between Class 0 and Class 3, indicating that while frequency can identify severe defects, it lacks sensitivity in distinguishing between adjacent classes, such as Class 0 vs. 1 or Class 1 vs. 3.
- Attenuation followed a similar trend to frequency, with only Class 0 vs. Class 3 comparison reaching statistical significance. This suggests that attenuation is effective for detecting major damage but is less reliable for identifying incremental changes in defect severity.

These findings reinforce the superior diagnostic value of ultrasonic velocity, which remains robust across all severity levels, whereas frequency and attenuation exhibit limited discriminative power except in the presence of severe defects. The combination of ANOVA and post-hoc testing thus provides a more nuanced understanding of how ultrasonic parameters respond to progressive structural degradation in wooden elements.

4 Limitations of the study

This study provides valuable insights into the relationship between ultrasonic properties and defect severity in wooden pillars. However, certain limitations must be acknowledged. the study focused on three Abies alba pillars of varying dimensions, which may limit the generalizability of the findings. Different wood species, densities, and moisture conditions could influence wave velocity and attenuation behavior, requiring further investigation with a broader sample set.

Measurement uncertainties also pose a limitation. Small transducer misalignments could introduce errors in time-of-flight calculations, affecting velocity and attenuation estimates. Additionally, the oscilloscope determines frequency through waveform analysis rather than direct measurement, leading to potential timing errors. Variability in impact force when striking the wood could further contribute to inconsistencies in the recorded data. Although multiple measurements were performed to minimize these uncertainties.

Experimental conditions may have also influenced the results. Wave reflections from surrounding surfaces and external vibrations could have distorted signal readings, while slight fluctuations in moisture and temperature, despite conditioning, may have affected velocity and attenuation measurements. Furthermore, the attenuation coefficient calculations relied on an estimated Q-factor range (20–50) for Abies alba, which may not fully account for natural variations in wood microstructure.

To address these limitations, future research should expand the study to include different wood species and structural configurations, implement automated transducer positioning, use a controlled impact mechanism, and conduct experiments in isolated environments to reduce signal interference and external noise.

Importantly, due to the limited sample size and inherent experimental constraints, the conclusions of this study should be considered preliminary rather than definitive. This acknowledgment is crucial not only for transparency but also to guide the interpretation and application of the findings by future researchers and practitioners.

5 Conclusions

This study examined the relationship between ultrasonic properties – wave velocity, frequency, and attenuation – and defect severity in wooden pillars. To conduct the research, three Abies alba pillars of varying dimensions were used, and acoustic measurements were employed to comprehensively assess their ultrasonic properties. The analysis differentiates between defect-free and defective regions, categorizing defect severity into distinct classes based on visible crack characteristics. The findings reveal that defects significantly affect ultrasonic wave propagation, with defective regions exhibiting lower velocities, reduced frequencies, and increased attenuation compared to defect-free areas. Among the evaluated parameters, wave velocity proved to be the most sensitive indicator of defect severity, showing a strong correlation with the structural integrity of the wood. Although frequency and attenuation offered additional insights, their sensitivity to defect severity was comparatively lower. Statistical analysis confirmed significant differences in ultrasonic properties between defective and defect-free regions, underscoring the effectiveness of ultrasonic testing as a reliable, non-destructive evaluation method for detecting defects in wooden structures.

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