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# Application of ultrasonic testing for the quantitative assessment of wood element degradation

Szymon Sawczyński[1], Piotr Bilko[2]

**ABSTRACT:**
The article presents the results of research on the possibility of using the ultrasonic method to assess the degree of degradation of wooden cross-sections, illustrated using floor beams originating from a 19th-century timber structure. Samples with various levels of cross-sectional damage were prepared by gradually removing layers of the material. Measurements were carried out in a direct transmission setup using a Pundit Lab+ device. The analysis results indicate a strong, non-linear relationship between ultrasonic wave velocity and the proportion of decayed wood in the cross-section, accurately described by an exponential function. Even a minor degree of cross-sectional degradation leads to a noticeable decrease in ultrasonic pulse velocity. The obtained relationships confirm the high effectiveness of ultrasonic testing as a non-destructive testing method for assessing the integrity of wooden sections, as well as its usefulness in the diagnostics of in-service structures, especially historical ones.

**KEYWORDS:**
ultrasonic testing; NDT; structural timber; structural diagnostics; wood decay

## 1. Introduction

Wood is an anisotropic material that exhibits significant variations in mechanical properties depending on the load direction relative to the fiber orientation. This difference results from the cellular structure of wood and its complex anatomical organization, comprising of both load-bearing elements and a system of pores responsible for moisture transport within the material. Increased moisture content and the development of microorganisms lead to material degradation, resulting in a reduction of the effective cross-section compared to its original dimensions.

In the renovation and diagnostics of heritage timber structures, assessing the condition of elements in situ is of key importance. Visual inspection and basic mechanical tests (the sclerometric method, drilling resistance measurement) constitute a preliminary stage enabling the identification of potentially weakened areas. However, these methods are qualitative in nature and require considerable experience from the investigator. The interpretation of results may be difficult, especially when degradation progresses inside the cross-section without clear symptoms on the element's surface.

Modern diagnostic methods for timber structures are evolving toward techniques that enable the most comprehensive possible assessment of material condition without interfering with its structure. These techniques serve to detect internal crack patterns, voids, and density variations [1-3], allowing the determination of the actual dimensions of structural elements required for accurate diagnostics [4]. In recent years, particular interest has been observed in wave-based

[1] University of Warmia and Mazury in Olsztyn, Faculty of Geoengineering, ul. Heweliusza 4, 10-724 Olsztyn, Poland, e-mail: sz.sawczynski@uwm.edu.pl, orcid id: 0000-0002-0297-1543
[2] University of Warmia and Mazury in Olsztyn, Faculty of Geoengineering, ul. Heweliusza 4, 10-724 Olsztyn, Poland, e-mail: piotr.bilko@uwm.edu.pl, orcid id: 0000-0001-5167-2470

methods, such as ultrasonics, stress waves, and acoustic tomography. Unlike resistance-based techniques, which are limited to local measurements along the drill line, ultrasonic testing allows for the evaluation of mechanical parameters over a larger portion of the cross-section. Numerous studies have confirmed that ultrasonic wave velocity is strongly correlated with mechanical properties such as modulus of elasticity and compressive strength [5-7]. Research has also demonstrated correlations for different wood species, ageing conditions, and moisture levels [8, 9]. Depending on the fiber orientation (longitudinal, radial, or tangential), ultrasonic waves propagate through wood at different velocities. Velocities in the longitudinal direction are the highest and range from 3050 m/s to 6100 m/s [10]. Radial and tangential velocities typically amount to approximately one-third of the longitudinal wave velocity, with the radial direction exhibiting slightly higher values than the tangential direction [11].

In response to challenges related to cultural heritage preservation, the literature reports increasing interest in non-destructive testing (NDT) methods, particularly elastic wave techniques. For example, the longitudinal modulus of elasticity is directly related to the propagation velocity of longitudinal elastic waves and material density, described by the equation:

$$E_{din} = v_L^2\,\rho \tag{1}$$

where $E_{din}$ represents the dynamic modulus of elasticity (N/mm$^2$); $v_L$ is the propagation velocity of the longitudinal stress waves (m/s), commonly denoted by UPV (ultrasonic pulse velocity), and $\rho$ is the density of the specimens (kg/m$^3$).

Biological degradation of wood – particularly the development of decay – leads to severe structural changes that significantly increase ultrasonic pulse travel time. Numerous studies [12-15] have shown that even minor degradation can cause a substantial reduction in wave velocity (Table 1).

The literature indicates that biological degradation of wood leads not only to weight loss or reduced density, but above all to morphological changes within the cell walls, which significantly disrupt the propagation of elastic waves in wooden elements. Studies show that even with limited internal degradation, the decrease in wave velocity may be considerable (Table 1) – often greater than would be expected from weight loss alone. This makes ultrasonic testing one of the most sensitive methods for detecting early stages of wood decay.

**Table 1**
Summary of studies on the use of wave propagation velocity to detect decay in wooden structures

| Wave transmission time versus of wood decay (µs/m) | Reference | | |
|---|---|---|---|
| | Hoyle and Pellerin 1978 [12] | Ross 1982 [14] | Volny 1992 [15] |
| Sound wood | 1,073.0 | 853.0 | 1,279.0 |
| Moderate decay | N/A | 1,276.0-2,129.0 | 1,827.0 |
| Severe decay | N/A | >3,280.0 | 2,430.0 |
| Decayed wood | 1,574.0 | N/A | N/A |

As shown in Table 1, wooden elements with intact cross-sections exhibit significantly shorter pulse travel times than those in which decay has developed. For healthy Douglas fir, these values average approximately 800 µs/m, whereas in elements with severely degraded cross-sections, transmission time may increase to 3200 µs/m or more.

In study [13], the effects of controlled fungal degradation on wood were analyzed. Depending on the exposure time to biological corrosion, changes were determined in, among others: weight loss, longitudinal stress-wave velocity ($v_L$), dynamic modulus of elasticity ($E_{din}$), and ultimate compressive strength ($UCS$). The results indicate that even a moderate mass reduction – on the order of 10 % – reflects a significant decrease in cross-sectional integrity, corresponding to approximately a 30 % loss in pulse velocity and about a 55 % loss of compressive strength (Fig. 1). A weight loss of around 35 %, characteristic of wood severely affected by decay, corresponds to reductions of approximately 50 % in pulse velocity and as much as 95 % in strength.

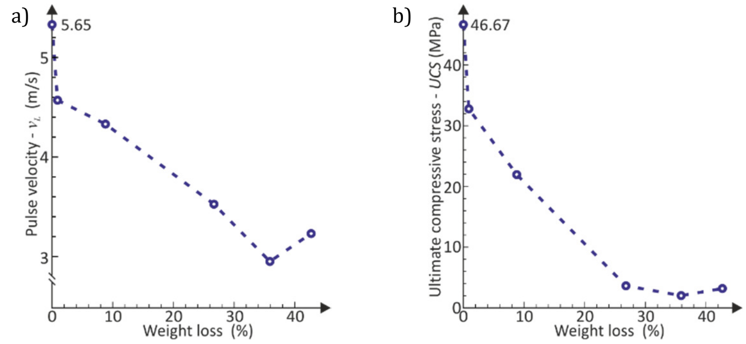


**Fig. 1.** Relationship between pulse velocity (a) and ultimate compressive stress (b) of wood versus and fungal degradation, based on [13]

From an engineering perspective, analysis of ultrasonic pulse velocity and travel time may provide valuable information enabling early identification of endangered structural areas that may show no visible effects of degradation. Measurements performed in the transverse direction (across the cross-section) are particularly effective in detecting areas of decay, as the wave cannot "bypass" degraded zones – an effect that often occurs during wave transmission parallel to the fibers. The use of ultrasonic techniques may provide invaluable support especially when assessing the technical condition of historical structures, where the possibility of intervening in the existing fabric is limited and the preservation of the original material substance is typically a priority. In the context of non-invasive diagnostics of timber structures, ultrasonic testing represents one of the most promising methods for the quantitative assessment of cross-sectional degradation and can significantly support decision-making regarding repair, strengthening, or replacement of structural elements during restoration processes.

## 2. Own research

### *2.1. Description of the tested samples*

The study involved fragments of pine floor beams originating from a 19th-century residential building (Fig. 2). Samples were collected during the revitalization of a historic townhouse. The elements exhibited advanced biological degradation typical of brown rot associated with high moisture content.

**Fig. 2.** View of a 19th-century historical building during revitalization works

a) b) c)

**Fig. 3.** Examples of degraded wooden beam fragments and cross-sections subjected to ultrasonic testing

## *2.2. Ultrasonic testing methodology*

Measurements were carried out using a Pundit Lab+ Ultrasonic Instrument. The unit consisted of a pair of wave transducers (transmitter and receiver) and a terminal/display station with data acquisition and Pundit Link software for data visualization and analysis. Testing was performed in a through-transmission setup, with the transducers placed on opposite sides of the sample, recording the travel time of the wave between the transmitting and receiving probes (Fig. 4).

**Fig. 4.** Measurements on the samples

This measurement configuration minimizes the contribution of surface waves and ensures maximum sensitivity to changes in the internal structure of the material. To ensure stable acoustic coupling between the probes and the wood surface, coupling gel was applied.

For each measurement the following were recorded: pulse travel time, propagation path length, visual and geometric description of the sample, and estimated percentage of decay within the cross-section.

Based on the recorded times and propagation distances, pulse velocities in the tangential direction were calculated. Results of the research are presented in Figure 5. A trend line was determined, which may be useful in the analysis of other beams.

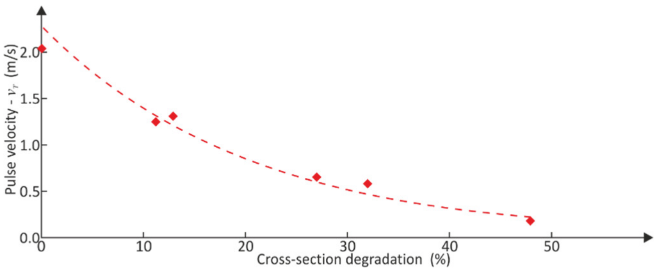


**Fig. 5.** Ultrasonic pulse velocity as a function of the cross-section degradation

The estimation of ultrasonic pulse velocity $v_T$ at successive degradation stages allowed the determination of a trend curve described by the exponential function:

$$v_T = 2.22\, e^{-3.77\, x} \tag{2}$$

where $x$ – proportion of decayed wood in the cross-section.

Equation (2) describes the nonlinear relationship between ultrasonic pulse velocity and the degree of cross-sectional degradation (Fig. 5). In the initial phase of wood degradation, i.e., up to approximately 20 % decay, the pulse velocity decreases rapidly, whereas beyond about 40 % degradation only moderate reductions were observed. The observations showed that even a slight decrease in pulse velocity relative to the reference value indicates a loss of structural integrity of the wooden element. From a practical standpoint, relationship (2), derived from propagation velocity measurements, may be used not only for detecting cross-sectional degradation but also for quantitatively estimating stiffness loss, which is crucial for assessing load-bearing capacity. It may signal the need for replacement or strengthening of structural elements during the renovation of historical buildings. Furthermore, attention is drawn to the high sensitivity of the ultrasonic method to the degradation of the internal structure, invisible on the surface of structural elements. The obtained results are consistent with literature reports concerning cell wall destruction and fiber discontinuity in advanced stages of wood decay.

## 3. Conclusions

Ultrasonic testing proved to be an effective method for detecting internal areas of degradation in wooden materials, even in cases where the external surface of the element remained intact. The obtained relationship between pulse velocity and the proportion of decay in the cross-section is exponential, indicating high sensitivity at advanced stages of degradation. The observations are consistent with results reported in studies for other wood species. This suggests the possibility of developing a universal model that allows the determination of cross-sectional degradation based on ultrasonic pulse velocity, considering species and density. The presented testing technique enables not only qualitative detection of destruction but also quantitative assessment of the degree of degradation of wooden elements, which is highly valuable in the context of evaluating structural load capacity.

The results may serve as a reference base for assessing in-service timber structures, particularly historical objects where sample extraction is impossible or undesirable due to the need to preserve original material. Interference with the structure may lead to irreversible loss of cultural heritage substance. The obtained results clearly confirm the high effectiveness of the ultrasonic technique in identifying macroscopically invisible degradation. The direct transmission setup increases the efficiency of detecting core destruction – typical of brown rot, though not limited to it.

The ultrasonic method for assessing wood condition enables detection of structural changes at an early stage, even before visible degradation occurs, and the results of this research indicate its potential for practical use as a decision-support tool in the renovation and reinforcement of timber structures.

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## Zastosowanie ultrasonografii do ilościowej oceny stopnia degradacji elementów drewnianych

**STRESZCZENIE:**
Przedstawiono wyniki badań dotyczących możliwości wykorzystania metody ultradźwiękowej do oceny stopnia degradacji przekrojów drewnianych na przykładzie belek stropowych pochodzących z XIX-wiecznej konstrukcji drewnianej. Próbki o zróżnicowanym stopniu zniszczenia przekroju przygotowano poprzez stopniowe, warstwowe usuwanie części przekrojów. Pomiary wykonano w układzie bezpośrednim z użyciem urządzenia Pundit Lab+. Wyniki analizy wskazują na silną, nieliniową zależność pomiędzy prędkością rozchodzenia się fali ultradźwiękowej a udziałem próchna w przekroju. Już niewielki stopień degradacji przekroju prowadzi do wyraźnego obniżenia prędkości impulsu fali ultradźwiękowej. Uzyskane zależności potwierdzają wysoką skuteczność ultrasonografii jako metody badań nieniszczących w ocenie integralności przekrojów drewnianych oraz jej przydatność w diagnostyce konstrukcji eksploatowanych, a w szczególności zabytkowych.

**SŁOWA KLUCZOWE:**
ultradźwięki; NDT; drewno konstrukcyjne; diagnostyka konstrukcji; próchno