# Non-destructive Testing of Wooden Elements

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# Non-destructive Testing of Wooden Elements

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**Abstract**. Examining the condition of wooden elements is crucial from the perspective of proper structure performance. If the deterioration in the internal wood condition, which displays no symptoms visible from the outside, is detected, the further spread of the deterioration can be prevented. Test results often point to the necessity of conducting repairs and, renovations, replacing the structure of wooden beams, or even substituting a significant part of the structure. To achieve acceptable results, test methods should take into account the anisotropic nature of wood, which includes the shape of annual rings, as well as the location of the core in cross-section. To adopt methods based on physical effects, profound knowledge of wood physics is needed, particularly of interdependence. Apart from simple tests such as a visual inspection or tapping that are used to determine near-surface defects, non-destructive testing (NDT) plays an important role in the process. This paper presents the methods of non-destructive testing of wooden elements. These methods include tests conducted with ground penetrating radar (GPR), thermal techniques, microwaves, acoustic emission, ultrasonic tomography, and X-ray tomography. The paper summarises the use of non-destructive methods, indicating their advantages, disadvantages as well as some limitations.

## 1. Introduction

Engineering structures are made using widely available materials, with wood being one of them for years. Its numerous advantages make it a material that was and still is often used. Wood is an easy-to-process material, as a result of which it is possible to form desired elements and shapes. It has good thermal and electrical insulation properties. The growing ecological awareness of the society also favours the use of this material. However, wooden elements of the structure undergo destructive processes over the years. The development and progress of such processes depend on various factors, including historical events that took place while the structure existed. Mechanical wear and long-term mechanical stress together with its consequences are those that result in the destruction of wooden elements. Wood is also subject to degradation under the influence of stresses from humidity changes and due to effects caused by insects. Fungal decay emerging when the humidity is above 20% is an important issue in the case of wooden objects in civil engineering. Besides, wood, due to its natural nature, suffers from internal or surface irregularities such as knots, grain slope, or resin pockets.

The easiest method of assessing the quality of wood is to perform a visual inspection. However, the destruction of wooden structures is not always visible on their surface. Wood that looks healthy at first glance may be damaged inside. It may have anomalies, defects, and biological damage affecting the mechanical properties of strength and stiffness, and may even lead to structure collapse, causing irreversible consequences. A good solution is to determine the quality of the wood by non-destructive testing. Such tests allow physical and mechanical properties to be identified. They make it possible to assess the occurrence of defects. Their advantage is that they do not interfere with the external structure of the element.

The proper determination of wood quality and precise detection of defects result in the optimisation of actions taken to repair a degraded structure, replace its parts, or, finally, replace the structure with a completely new one.

## 2. Wood properties

Wood is a biomaterial that consists of cellulose, lignin, and hemicellulose. It is characterised by a much greater variety than concrete, metal, or plastic. The determination of wood properties is more complex than for other building materials. The anisotropy of mechanical properties is one of the qualities of wood. Other wood qualities include high strength parallel to the grain, but considerably lower strength in the perpendicular direction. With this in mind, strength, stiffness, and other properties should be determined individually for each element.

Inevitable wood defects such as cracks or knots are another complication. Two models of anisotropy can be used to describe the elastic properties of wood: transverse-isotropic or orthotropic. The first one is described by five independent elasticity constants, while the second one by nine. For comparison, the isotropic body model, which is used to describe most building materials, is characterised by only two elastic constants. The orthotropic body model is a more accurate model for describing the properties of wood.

**Figure 1.** Example of the use of wood in the construction of a ceiling.

The orthotropic model features the existence of three mutually perpendicular planes of elastic symmetry, i.e. such that in any two directions symmetrical to them, the material properties are the same. In the case of wood, these planes result from the structure of the wood and are determined by the anatomical directions of this material: longitudinal L, radial R, and tangential T.

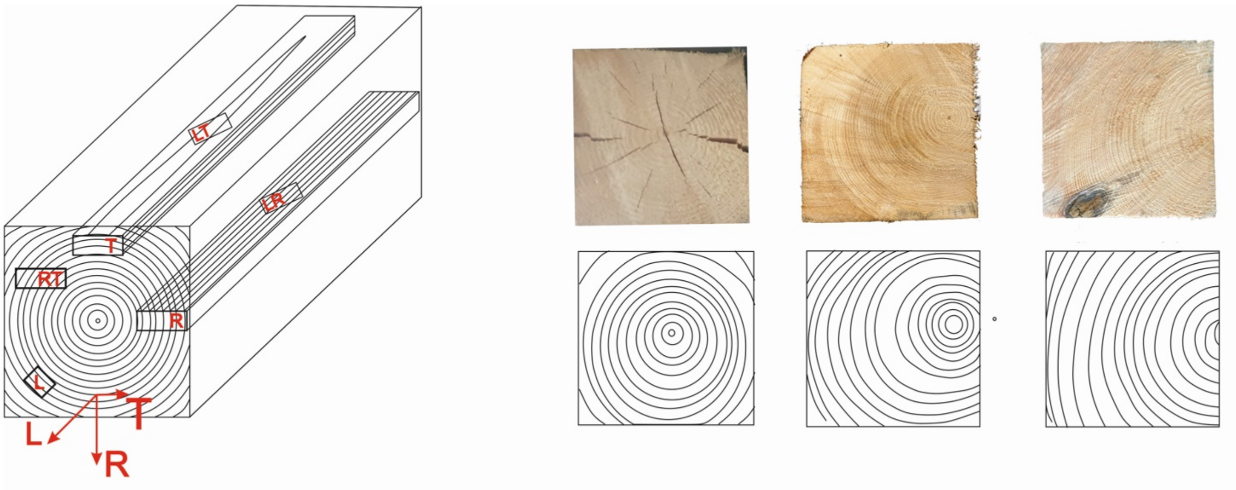


**Figure 2.** Wood anatomic axis and wood fracture systems: longitudinal (L), radial (R), and tangential (T) directions (a). Wooden beams with the variable location of the cross-section core (b).

The following relationships between the components of the state of deformation and stress can be written in the LRT coordinate system:

$$\begin{cases} \varepsilon_L = \dfrac{1}{E_L}\sigma_L - \dfrac{\nu_{RL}}{E_R}\sigma_R - \dfrac{\nu_{TL}}{E_T}\sigma_T \\ \varepsilon_R = -\dfrac{\nu_{LR}}{E_L}\sigma_L - \dfrac{1}{E_R}\sigma_R - \dfrac{\nu_{TR}}{E_T}\sigma_T \\ \varepsilon_T = -\dfrac{\nu_{LT}}{E_L}\sigma_L - \dfrac{\nu_{RT}}{E_R}\sigma_R + \dfrac{1}{E_T}\sigma_T \\ \gamma_{LR} = \dfrac{1}{G_{LR}}\tau_{LR} \\ \gamma_{RT} = \dfrac{1}{G_{RT}}\tau_{RT} \\ \gamma_{LT} = \dfrac{1}{G_{LT}}\tau_{LT} \end{cases} . \tag{1}$$

$$\frac{\nu_{LR}}{E_L} = \frac{\nu_{RL}}{E_R}, \quad \frac{\nu_{LT}}{E_L} = \frac{\nu_{TL}}{E_T}, \quad \frac{\nu_{RT}}{E_R} = \frac{\nu_{TR}}{E_T}. \tag{2}$$

where:
- $E_L, E_T, E_R$ – Young's modulus in direction L,T, and R respectively

- $\nu_{ij} = \dfrac{\textit{unit deformation along the axis i}}{\textit{unit deformation along the axis j}}$ with uniform normal stress in the direction of axis i; $i \neq j; \quad i,j = L,R,T$
- $G_{ij}$ –shear modulus in-plane $ij, \; i \neq j; \quad i,j = L,R,T; \quad G_{ij} = G_{ji}$

## 3. Non-destructive tests

By definition, non-destructive testing (NDT) makes it possible to verify the condition of the existing structure, to predict its durability, and to assess the quality of workmanship and safe use. The most important advantage of NDT is the ability to establish parameters and a detailed physical description of the tested material at each stage of the structure's existence. The parameters of wooden elements that can be determined using non-destructive methods are listed in Table 1 along with the methods that can be used to determine them.

**Table 1.** Overview of available non-destructive testing methods for wood [1-2]

| Parameters / material state | Methods |
|---|---|
| Modulus of elasticity | Ultrasound |
| Density | Ultrasound, X-ray, Microwave, Resonance (NMR), Drilling, Electromagnetic methods |
| Moisture | X-ray, Microwave, Resonance (NMR), Electromagnetic methods |
| Layer thickness measurement | Optical, Electromagnetic methods |
| Inhomogeneity | Ultrasound, Acoustic emission, X-ray, Microwave, Resonance (NMR), Electromagnetic methods, Thermography, Microwave, Visual inspection |
| Cracks | Ultrasound, Acoustic emission, X-ray, Thermography, Visual inspection |
| Decay | Ultrasound, X-ray, Thermography, Visual inspection |
| Failure | Acoustic emission, Thermography |
| Deformations | Optical laser, Acoustic emission, Visual inspection |
| Stiffness | Ultrasound |

### *3.1. Optical methods*

This method use measurement techniques based on testing equipment such as endoscopes, borescopes, videoscopes, or microscopes. These instruments allow surfaces and places inaccessible to the naked eye to be examined. Such tests also include techniques that use laser scattering to mark the location of points in three dimensional space. Optical methods make it possible to assess displacements, vibrations, and surface deformations in a non-*contact manner*.

### *3.2. Electromagnetic methods*

Electromagnetic methods are primarily used to determine the thickness of the element accessible from one side and to identify and locate delamination and defects. The most popular method based on electromagnetic (EM) properties is the ground-penetrating radar method (GPR). Due to the ability to test large areas in a short time, this method is often used for large areas of reinforced concrete structures [3] or floors [4-5].

The GPR method involves emitting electromagnetic waves to the investigated medium. The measurement of the relative permeability of wood is based on the microwave technique, which involves the propagation of electromagnetic waves from the antenna in two configurations – transmission or reflection. The reflection method is used more frequently. Wood is considered a slightly conductive material that permits the propagation of electromagnetic waves. Therefore, it is characterised by dielectric permittivity, which can be written in real and imaginary terms. The real part of complex thermal transmittance is known as the dielectric constant, while the imaginary part is the loss factor. During measurements, the GPR is moved along the tested surface and for each position, a single GPR route is measured (Fig. 3). The basic imaging used in the GPR method is the GPR map, also known as an echogram or radargram, the so-called B-scan, consisting of individual time signals recorded at successive points in space forming a spatial and temporal plane.

It is well known that the propagation of electromagnetic waves in wood is dependent on humidity, temperature, density, as well as the species and type of wood. One of the most important factors affecting electrical properties is humidity [6-8]. The dielectric properties of wood are cylindrically orthotropic. They are determined in relation to three generally accepted directions: longitudinal (L), radial (R), and tangential (T). The main limitation of the GPR for use in wooden elements is the difficulty in finding small-sized defects. In this case, acoustic methods will be more appropriate.

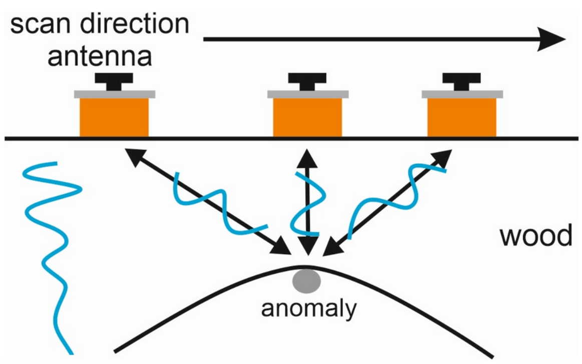


**Figure 3.** The scheme of surveys using the GPR method.

### *3.3. Acoustic methods*

These methods are among the most common non-destructive methods used to analyse wood properties. These include ultrasound methods, impulse response method, ultrasonic tomography, and acoustic emission. Each of these methods is based on the propagation of elastic waves through a structural element.

Ultrasonic methods are used to test strength and homogeneity indirectly. They allow material discontinuities and the occurrence of air voids and cracks to be determined. They are based on the propagation of ultrasound elastic waves through the element. It is mainly used in metal, concrete [9], and masonry elements [10]. However, they are starting to play an increasingly important role in the diagnosis of wooden structures. In the case of wood, the velocity of elastic waves is strictly dependent on the grain direction. Elastic properties such as dielectric properties are set separately for the longitudinal (L), radial (R), and tangential (T) directions. The signal is emitted by the transmitter and read by a receiver situated on the same surface – in the case of the diffraction method – or on the opposite surface – in the case of the transmission method. An elastic wave passing through an element undergoes reflections and penetrates the boundary of media with different values of modulus of elasticity and density. The intensity of reflection and wave penetration depends on the value of the acoustic impedance of the neighbouring media, defined as the product of the density and propagation velocity of an elastic wave in a medium. In the case of media with different acoustic impedance values, part of the energy goes to the adjacent medium, while the rest is reflected. In the case of a small difference in acoustic impedance, a significant part of the wave passes into the adjacent medium. A large difference in the acoustic resistance of the media can cause the complete reflection of the wave.

Ultrasonic measurements are often used to create tomographic maps. A map presenting the distribution of a specific parameter, for example, the wave propagation velocity, is created based on the above-mentioned values, which facilitates the interpretation of information on the examined area. In wooden elements, the map shows the cross-section core and material discontinuities (Fig. 4).

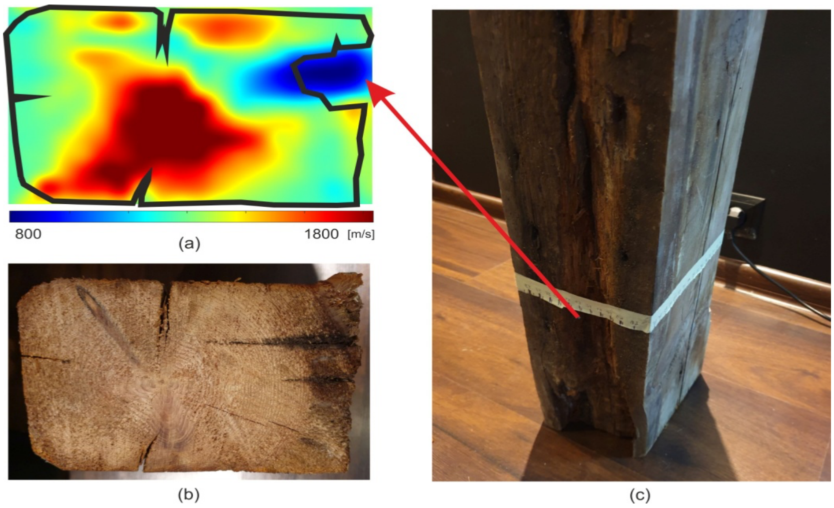


**Figure 4.** Ultrasonic tomography map of a wooden beam (a), beam top view (b), beam view (c).

The acoustic emission method uses the propagation of high-frequency elastic waves resulting from the effect of a static, dynamic, multiple-variable load and a non-mechanical load. It is a passive method based on naturally occurring stress waves generated by an internal failure. The acoustic emission method is often integrated with monitoring systems of a given structure because excitation is released from the inside of the tested element and not as an external acoustic impulse. Tests with the use of acoustic emissions are also carried out on wooden elements [11-13]. This method allows the destruction process of a given element to be signalled early, making it possible to take sufficient and quick action. At the same time, the disadvantage of this method includes the difficulty in distinguishing AE signals from those originating from external noise and the limited applicability of the method in the case of large-sized structures.

### *3.4. Thermography*

Thermography is a test that involves the measurement of the temperature distribution on the surface of the tested element. It is currently the most popular method of object diagnostics, using the detection of infrared radiation in the range of 3–5 μm (SWIR - short-wave thermal imaging) or 8-12 μm (LWIR - long-wave thermal imaging). This technique is classified as non-destructive. In thermographic techniques, it is necessary to know the emissivity of the tested object, the value of which varies in the range of 0–1 and which determines the ability of the tested surface to emit radiation, taking into account the surface condition (roughness), the type of material it is made of, and the wavelength of the radiation in which thermal imaging equipment operates. The higher the value of the emissivity coefficient, the more energy the tested object emits and the more contrasting the thermal image is. In the case of wooden elements, thermography is used to test wood density [14], but also to detect material voids and discontinuities [15].

### *3.5. X-ray tomography*

High-resolution X-ray imaging is a powerful technique that allows the internal structure of wood to be examined without damaging it. This method is based on recording the projection of an object with a beam of X-rays passing through it. For years, X-ray tomography has been used for medical purposes, but it is also increasingly being used in the field of engineering. X-ray tomography is the collection of multiple X-ray images of an object from different viewing angles in order to reconstruct a cross-section. A 3D view can be obtained by scanning an object piece by piece. The tomography image is shown in grayscale depending on the attenuation of X-rays, which is related to the atomic number and the number of atoms in the beam path. The atomic composition of wood is relatively constant, and the radiography of a wood sample of constant thickness mainly depends on changes in density. X-ray sources generate divergent beams. Measurements are made on samples of the collected elements. The disadvantage of using radiography is that the device takes up a lot of space and requires special protection on all sides against X-rays. [16]

## 4. Conclusions

In this paper, the most common non-destructive testing methods used to evaluate wooden elements were presented. The variability of wooden elements requires an individual approach to structures of this type. Non-invasive diagnostics can provide a lot of valuable information on important parameters of wood resulting from its mechanical properties. In general, the best results are obtained using multisensor techniques. A single parameter is usually insufficient for a concise description of the state of the material; therefore, the combination of several measuring methods is an effective solution. The GPR measurement is an effective method used to determine the dimensions of elements, while ultrasonic methods are used to detect small defects.

For many years, the analysis of the strength characteristics that determine the safe use of the structure has been constantly developed and improved. The constant development of non-invasive techniques is used to improve the quality of testing and assessing building structures with the required accuracy.

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