infrastructures

MDPI

Review

Review of Nondestructive Testing (NDT) Techniques for Timber Structures

Ziad Azzi [1], Houssam Al Sayegh [2,*], Omar Metwally [2] and Mohamed Eissa [2]

[1] Director of Engineering, DDA Forensics, Miami, FL 33178, USA; ziad@ddaforensics.com
[2] Department of Civil and Environmental Engineering, Florida International University, Miami, FL 33174, USA; ometw001@fiu.edu (O.M.); meiss002@fiu.edu (M.E.)
* Correspondence: halsa037@fiu.edu

Abstract: The widespread adoption of wood in construction is driven by its sustainability, cost-effectiveness, and esthetic appeal. The construction of wood buildings often requires minimal specialized equipment, contributing to affordability and higher demand for wood-frame structures. Wood is considered more sustainable than other building materials, such as steel or concrete, for several reasons, including its renewable nature, low embodied energy, carbon sequestration, energy efficiency, and biodegradability, among others. In the United States, wood is the most common material used in building construction. While many of the structures are single-family homes, wood framing is also prevalent in larger apartment complexes, as well as commercial and industrial buildings. Timber has also been traditionally used for bridge construction, and recently, it has been considered again for the construction of new bridges. Over time, wood-frame construction has developed from a basic method for primitive shelters into a sophisticated field of structural design. As an eco-friendly resource, wood is crucial for promoting sustainable building practices. However, ensuring the long-term performance and safety of timber structures is essential. Regular inspections and testing of wooden structures are important to identify signs of wear, damage, or decay. One type of testing which is gaining popularity is nondestructive testing (NDT). NDT techniques have become invaluable for assessing the condition of timber components because such techniques are non-invasive in nature and do not cause damage, ensuring that structures remain functional with minimal disruptions. These methods provide critical insights into the structural integrity and operational efficiency of wood under sustained loads and in inclement environments. This article examines various NDT techniques used to evaluate timber structures, highlighting their capabilities, as well as advantages and limitations. It also discusses the importance of wood in advancing sustainability within the construction industry and emphasizes the need for accurate and reliable assessment methods to enhance the use of timber as an environmentally friendly building material. By incorporating NDT practices into regular inspection and maintenance protocols for buildings, bridges, and other structures, various stakeholders can ensure the durability, longevity, and safety of timber structures, thereby contributing to the progress and advancement of sustainable construction practices worldwide.

Keywords: wood; timber; nondestructive techniques (NDT); sustainability; inspection; structural integrity; safety; sustainable construction practices

Academic Editor: Joan Ramon Casas Rius

Received: 27 November 2024
Revised: 13 January 2025
Accepted: 16 January 2025
Published: 22 January 2025

Citation: Azzi, Z.; Al Sayegh, H.; Metwally, O.; Eissa, M. Review of Nondestructive Testing (NDT) Techniques for Timber Structures. *Infrastructures* **2025**, *10*, 28. https://doi.org/10.3390/infrastructures10020028

1. Introduction

Wood is a sustainable, cost-effective, and visually appealing material that has been extensively utilized in civil engineering structures for many years. As the most plentiful renewable building resource provided by nature, wood is a prevalent structural material in North America, where it constitutes 90% of all residential buildings [1]. The application of wood in construction includes residential buildings, retail spaces, offices, hotels, educational institutions, healthcare, recreational facilities, senior living and retirement homes, and places of worship. The most frequently encountered wood structures are residential and multi-family dwellings, along with hotels. Typically, residential buildings range from one to three stories in height, while multifamily and hotel structures can extend up to five or six stories, with wood framing the upper floors and steel or concrete framing the lower levels. Wood is generally not used for commercial, industrial, or institutional structures with higher occupancy loads and safety factors, though it might be employed as a secondary structure, such as for storage mezzanines [2]. The common structural elements used in timber buildings are illustrated in Figure 1.

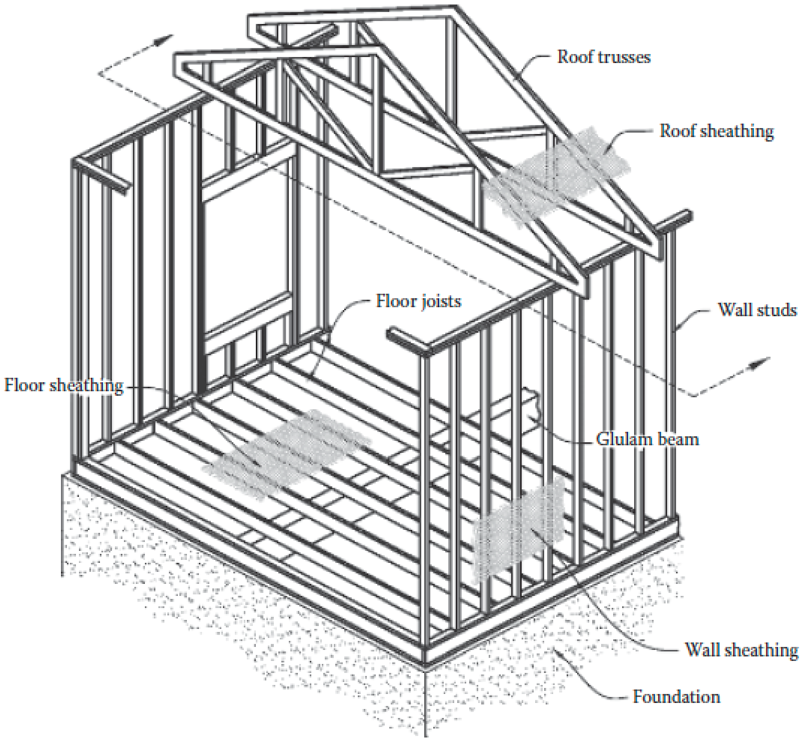
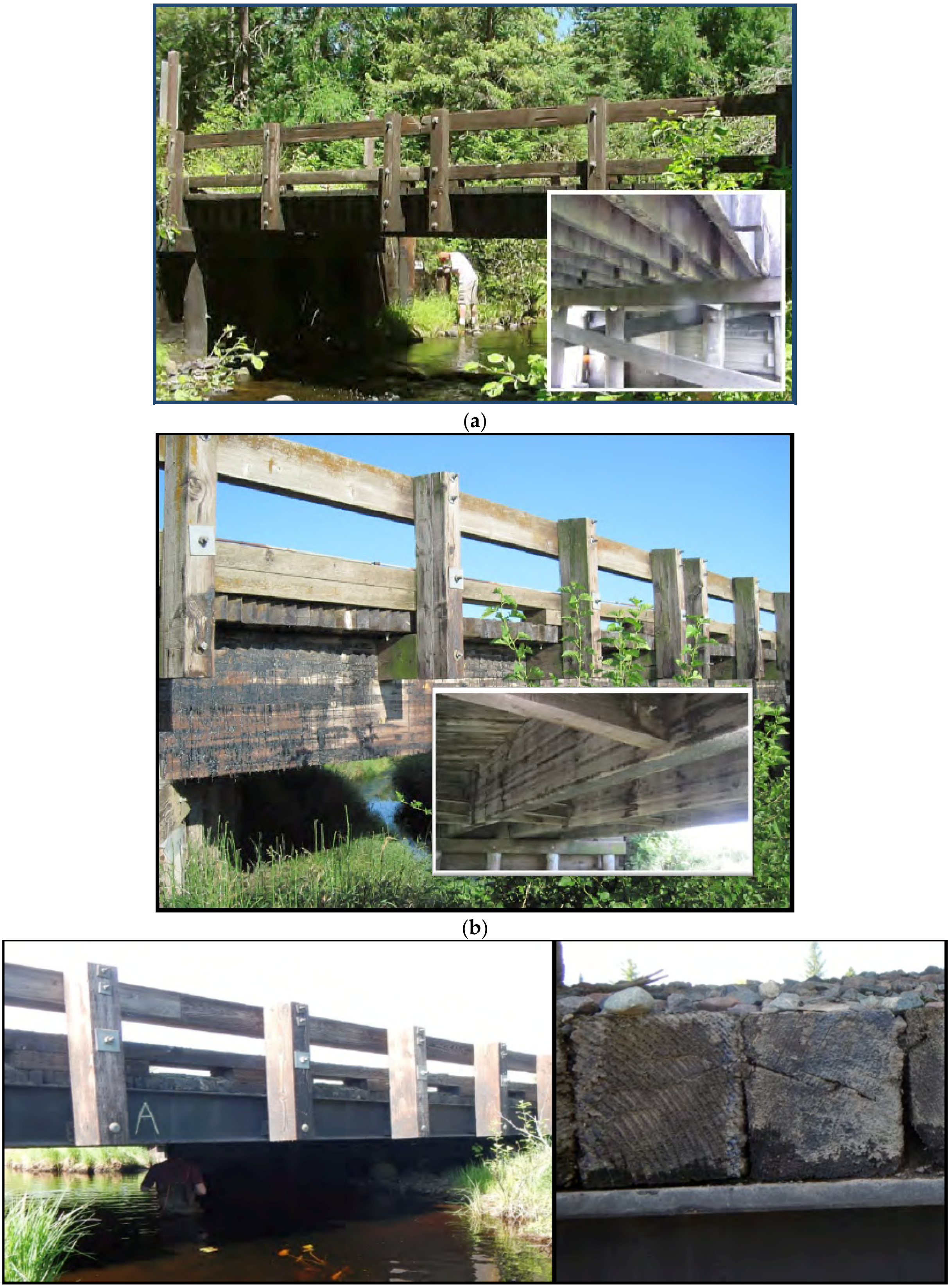


Figure 1. Typical structural elements (Courtesy of Aghayere & Vigil [1]).

Additionally, wood has been a widely used material in bridge construction, particularly for bridges built during the 1950s and 1960s [3]. The Federal Highway Administration (FHWA) national bridge inventory indicates that there are over 576,000 bridges in the United States with spans of 6 m (20 feet) or more. Among these, 41,740 timber bridges exceed this span length and are still in use today. Additionally, another 42,100 bridges feature timber decks supported by steel stringers, categorizing them as steel bridges. Due to their relatively younger age compared to steel and concrete bridges, many timber bridges require repair or replacement due to identified or suspected deterioration [4]. Therefore, accurately assessing the current condition of a bridge is crucial for determining the appropriate load rating and making informed decisions regarding rehabilitation, repair, or replacement. Proper knowledge of a bridge's condition can result in cost savings by reducing the need for extensive labor and materials while extending its service life. As such, the safe and efficient functioning of the U.S. transportation system heavily relies on the performance and upkeep of vehicular bridges. Figure 2 illustrates examples of timber bridges constructed with sawn lumber, glulam, and steel/wood composite sections.



(**a**)

(**b**)

(**c**)

Figure 2. Examples of timber bridges constructed with (**a**) sawn lumber, (**b**) glulam timber, and (**c**) steel/wood composite section (Courtesy of Brashaw et al. [5]).

In general, wooden elements are subject to destructive processes over time. The development and progression of these processes depend on various factors, including historical events experienced by the structure. Mechanical wear and long-term mechanical stress, along with their consequences, contribute significantly to the deterioration of wooden elements. Wood also degrades under stress from humidity changes and insect activity. Fungal decay, which occurs when humidity exceeds 20%, is a critical issue for wooden structures in civil engineering. Additionally, wood inherently suffers from internal or surface irregularities such as knots, grain slopes, or resin pockets. Due to their use in residential buildings and bridges, timber structural elements are often exposed to harsh environmental conditions and adverse weather. This exposure over time can lead to deterioration, causing staining, decay, insect infestation by wood-destroying organisms (WDO), weathering, and mechanical damage. Such deterioration can compromise the structural integrity, posing risks to the structure and its occupants [6].

Nondestructive testing (NDT) of materials involves identifying the physical and mechanical properties of a material without compromising its future usability. NDT was first used during the Industrial Revolution as a primary inspection technique to assess materials and has undergone significant evolution since its inception. The rapid industrialization of this era necessitated efficient methods for ensuring the reliability of materials used in manufacturing and infrastructure. Early practices relied heavily on visual inspection and basic mechanical tests, which, although useful, were limited in scope and accuracy.

The early 20th century marked a turning point for NDT, with the advent of World Wars I and II spurring rapid advancements in inspection technologies to meet military demands. X-ray radiography, adapted from medical imaging, became a vital tool for detecting internal defects in metals, ensuring the structural integrity of critical components like aircraft and naval vessels. Ultrasonic testing (UT) also emerged during this period, offering a groundbreaking method for identifying internal flaws. A significant milestone in UT technology was Floyd Firestone's invention of the Supersonic Reflectoscope, a device designed to inspect solid materials using sound waves, as detailed in his seminal research [7].

By the 1960s and 1970s, NDT had evolved into a recognized professional discipline. During this era, the establishment of standardized methodologies, certification programs, and structured training systems enhanced the reliability and consistency of NDT practices. This professionalization coincided with a broadening of NDT's scope to include non-metallic materials like plastics, ceramics, and composites, reflecting the diverse needs of modern engineering and manufacturing industries [8].

The late 20th century brought transformative advancements in computing and sensor technologies, revolutionizing NDT techniques. Innovations like digital radiography enhanced image clarity and reduced reliance on traditional film-based methods. Similarly, acoustic emission testing enabled real-time monitoring of structural integrity, while ground-penetrating radar (GPR) extended NDT applications to infrastructure and geological studies.

Over the past five decades, forest products researchers and the forest products industry have developed and utilized NDT tools for various applications, ranging from grading structural lumber to evaluating the mechanical properties of individual members in wood structures [9,10]. Nondestructive testing techniques for wood differ significantly from those used for homogeneous, isotropic materials such as metals, glass, plastics, and ceramics. In these non-wood-based materials, with mechanical properties that are well-known and tightly controlled by manufacturing processes, NDT techniques are used to detect discontinuities, voids, or inclusions. Since wood is a biological material, it naturally contains irregularities that can be exacerbated by environmental degradation. Therefore, NDT techniques for wood measure how these natural and environmentally induced irregularities interact within a wood member to determine its mechanical properties [10].

The aim of this paper is to (i) briefly introduce the reader to the physical properties of wood and how they are affected with the passage of time as well with exposure to the weathering elements; (ii) present the commonly observed instances of damage to timber structures including natural defects as well as defects due to stresses, loads, and cyclic movements; (iii) introduce the different NDT methods to date along with their potential applications including their advantages, and drawbacks; and (iv) offer a potential guide for the selection of NDT methods for inspectors conducting field investigations of timber structures.

2. Defects and Damage in Timber

Timber, a natural and versatile construction material, exhibits a range of defects and damage instances due to its organic origin and the environmental and mechanical stresses it endures. Understanding these defects is crucial for the effective operation and maintenance of timber structures used in buildings and bridges or other structures. This section delves into the common defects observed in timber structures, categorized into natural defects and defects due to stresses and loads.

2.1. Natural Defects Inherent in Wood

The most occurring defects are natural defects in timber; they arise from the inherent characteristics and growth patterns of trees. These defects include knots, shakes, splits, and grain deviations, which significantly influence the physical and mechanical properties of timber.

Knots: Knots are portions of branches that become embedded in the tree's trunk as it grows. They are classified based on their position (e.g., intergrown and encased) and appearance (e.g., live and dead). Knots disrupt the uniformity of wood, affecting its strength and esthetic appeal. The presence of knots can create weak points in timber, leading to potential failure under stress. Additionally, they can impede machining processes and affect the finish quality of timber products [11]. An example of knots and other wood defects are presented in Figure 3.

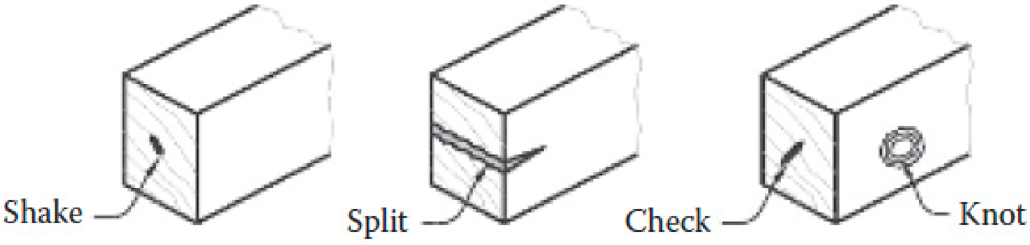


Figure 3. Examples of shakes, splits, checks, and knots (Courtesy of Aghayere & Vigil [1]).

Grain Deviations: Grain deviations, including cross grain, spiral grain, and interlocked grain, occur when the wood fibers do not run parallel to the longitudinal axis of the timber. These deviations can result from the tree's growth response to environmental stresses such as wind or uneven terrain. Grain deviations affect the strength properties of timber, particularly its bending and tensile strength, making it more prone to warping and cracking [12].

Reaction Wood: Reaction wood forms in response to mechanical stresses on the tree, such as leaning or bending. It includes compression wood in conifers and tension wood in hardwoods. Reaction wood exhibits abnormal properties, including higher density and shrinkage, which can lead to uneven drying and increased susceptibility to warping and splitting [13].

Biological Defects: Biological defects arise from fungal and insect activity. Fungal decay, such as white rot and brown rot, can significantly reduce the strength of timber. Insect damage, including termite and beetle infestations, can create tunnels and voids within the wood, compromising its structural integrity. These biological defects are often not visible on the surface, making early detection and prevention crucial for maintaining timber structures [13].

Shakes and Splits: Shakes are separations along the grain of the wood, typically caused by growth stresses or environmental factors such as frost. There are various types of shakes, including heart shakes, star shakes, and ring shakes. Splits are similar to shakes but generally occur due to mechanical damage during felling, handling, or drying. Both defects can compromise the structural integrity of timber, leading to potential failure under load [11,14].

2.2. Defects Due to Stresses and Loads

Timber structures are subject to various stresses and loads throughout their service life, which can lead to defects and damage due to fatigue. These include mechanical stresses from loads, moisture-induced stresses, and thermal stresses.

Stresses Perpendicular to Grain: Timber is an anisotropic material, meaning its properties vary with direction. It exhibits significantly lower strength perpendicular to the grain compared to parallel to the grain. Stresses perpendicular to the grain can arise from load-bearing situations or environmental factors, leading to splitting and checking. These defects are critical as they can significantly reduce the load-carrying capacity of timber elements [13,15].

Moisture-Induced Stresses: Timber is hygroscopic, meaning it absorbs and desorbs moisture from the environment. Changes in moisture content cause timber to expand and contract, leading to moisture-induced stresses. These stresses are more pronounced perpendicular to the grain, where dimensional changes are greater. Prolonged exposure to high moisture levels can lead to swelling, while drying can cause shrinkage, resulting in cracks, checks, and warping. Proper moisture management and protection measures are essential to mitigate these defects [13,15].

Creep and Duration of Load (DOL) Effects: Creep is the gradual deformation of timber under sustained load. The magnitude of creep depends on factors such as stress level, moisture content, and temperature. Higher stress levels and cyclic moisture changes can accelerate creep, leading to increased deformation over time. Duration of Load (DOL) effects refer to the reduction in strength and stiffness of timber under prolonged loading. These effects are critical in the design and maintenance of timber structures, as they can lead to excessive deflection and potential failure under sustained loads [9,13].

Thermal Stresses: Although timber has relatively low thermal conductivity, it can still experience thermal stresses due to temperature changes. These stresses can cause expansion and contraction, leading to checking and splitting. Thermal stresses are particularly relevant in situations where timber elements are exposed to direct sunlight or significant temperature variations. Adequate ventilation and protection from direct heat sources can help mitigate thermal stresses in timber structures [13].

Mechanical Damage: Mechanical damage to timber structures can occur during handling, transportation, or installation. Common forms of mechanical damage include impact damage, crushing, and abrasion. These defects can create weak points and reduce the load-carrying capacity of timber elements. Careful handling and proper installation techniques are essential to prevent mechanical damage and ensure the longevity of timber structures [13,14].

All in all, timber structures are subject to various natural defects and defects due to stresses and loads. Natural defects such as knots, shakes, splits, grain deviations, and reaction wood arise from the inherent characteristics of trees and can significantly affect the strength and durability of timber. Defects due to stresses and loads, including stresses perpendicular to the grain, moisture-induced stresses, creep, DOL effects, thermal stresses, and mechanical damage, result from environmental and mechanical factors that timber structures encounter throughout their service life.

3. Commonly Used NDT Methods for the Inspection of Buildings and Bridges

NDT techniques enable the inspection of materials or components without compromising their functionality or future utility. While some structural components are accessible, others, such as reinforced concrete elements and enclosed connections, are not. Due to the limited accessibility of these components, regular inspection is not feasible, necessitating the use of more advanced NDT techniques [16–20]. These techniques are essential for identifying, locating, measuring, and evaluating defects to determine the integrity, properties, and composition of the materials.

When applied to wood, NDT methods assess how natural and environmentally induced irregularities affect the mechanical properties of a wood member. A diverse array of NDT methods has been developed and utilized specifically for wood and structural timber evaluation. The fundamental hypothesis for NDT of timber was first proposed by [21]. The author investigated how wood properties interact with various energy forms, such as sound waves and electromagnetic radiation, demonstrating that statistical methods can establish valuable correlations between NDT parameters and the strength of wood elements. This idea paved the way for the development and enhancement of numerous NDT techniques, which have since become effective tools for the precise and dependable evaluation of wood materials.

While this section focuses on NDT methods, specifically applicable to wood elements, it is worth noting that NDT methods for other types of structural materials have been extensively discussed by others and can be referenced for further details [22–30]. Some of these methods can also be adapted for use in wood structures. For example, ref. [20] demonstrated the effectiveness of a procedure called the Precursor Transformation Matrix (PTM) in detecting damage in external tendons of post-tensioned bridges. This method could accurately identify the location of global damage with fewer inspections, potentially avoiding the need for costly and time-consuming NDT methods on a larger scale. The PTM approach could also be beneficial for wood truss structures, such as wood truss bridges. In the following section, several NDT methods with direct applicability for timber will be grouped together and elaborated in greater detail based on their applications.

3.1. Visual Inspection

Visual inspection is among the most fundamental and widely used NDT techniques for assessing the condition of wood. This method involves a thorough examination of the wood's surface to detect any visible signs of defects, damage, or deterioration. Although it is limited to identifying surface-level and near-surface issues, visual inspection remains invaluable due to its straightforwardness, cost-efficiency, and the essential preliminary insights it offers regarding the wood's structural health and integrity. Additionally, visual inspection plays a key role in identifying areas that may require more in-depth analysis with advanced NDT methods.

A comprehensive visual inspection of wood requires specific tools such as magnifying glasses, a flashlight, a measuring tape or ruler, marking tools for noting defects, and a mirror for viewing hard-to-reach areas. Surface probing for signs of deterioration can be carried out using tools like a gimlet, awl, or chisel, while a hammer may be employed to tap the wood and detect internal voids. Measuring moisture content is essential, and for this, a hygrometer and moisture meter are necessary. A digital camera is also useful for documenting observations. For inspecting cavities and boreholes, a borescope or videoscope can provide critical insights.

A thorough visual inspection of timber structures begins with an initial walk-through to gauge the overall condition and prioritize preservation efforts. This includes identifying key structural components, determining the wood species, and assessing moisture levels and potential biodeterioration risks. Inspectors may conduct geometric surveys to record any dimensional or shape variations. Areas exhibiting significant defects or decay are flagged for further detailed evaluation of their structural performance. Access to the timber elements is crucial, often necessitating the use of scaffolding, surface cleaning, and proper lighting. The information gathered from this methodical inspection guides the planning of subsequent nondestructive testing and provides critical data for structural analysis and possible repairs. More information about this specific procedure can be found in [31].

3.2. Scan to BIM

The 3D laser scanning combined with Scan to BIM (Building Information Modeling) represents a cutting-edge approach to assessing the condition of structures without causing further damage. The process involves using LiDAR (Light Detection and Ranging) to capture high-resolution, three-dimensional data points of a structure, producing a precise "point cloud" that accurately reflects its geometry and condition. This non-intrusive method is particularly valuable in post-damage scenarios, such as after fires or natural disasters, where maintaining structural integrity during assessment is critical. The point cloud data can be processed into a BIM-compatible model, creating a digital twin of the structure that allows for detailed visualization of damage, such as cracks, deformation, or material loss, without physically probing or removing components. Unlike traditional NDT techniques, which might focus on specific localized areas, 3D laser scanning provides a comprehensive view of the entire structure, including hard-to-access zones. This allows inspectors to identify damage patterns, monitor structural health over time, and plan restorations with unparalleled accuracy. Moreover, by avoiding physical intrusion, it minimizes risk to both the structure and personnel, making it an ideal NDT method for sensitive or compromised environments. More details about this method can be found in [31].

3.3. Moisture Content Measurement

The estimation of wood moisture content (MC) is crucial for grading and calibrating NDT results, as high MC is associated with bio-deterioration risks such as insect infestation and wood decay fungi growth. MC in structural timbers is generally not uniform and can vary along the length and cross-section. The methods for estimating MC include the resistance method, the capacitance method, and the hygrometric method.

3.3.1. The Resistance Method

This technique relies on the correlation between the MC and the electrical resistance, utilizing hand-held moisture meters that operate on the resistance principle. These meters, calibrated with samples of known MC, employ insulated electrodes to gauge localized moisture levels. The electrodes are inserted into the wood, and measurements are taken at different depths and locations. As the moisture content increases, the electrical resistance decreases due to the fact that water is a conductor of electricity, whereas wood is not. This method is effective for measuring MC in the range of 7% to 30% and requires adjustments based on wood species and temperature variations. Therefore, temperature has to be measured simultaneously with the measurement of the MC. Additionally, the main drawback is that this method reports a local measurement and, therefore, requires a lot of sensors to efficiently report the MC across the investigated element. Figure 4 shows a schematic for using the resistance method. Two types of electrodes are shown in the schematic. Insulated electrodes (on the right) will only measure the MC at the tip, which is preferred since it allows local estimation of MC. Non-insulated electrodes (on the left) will measure the highest MC along the embedded length.

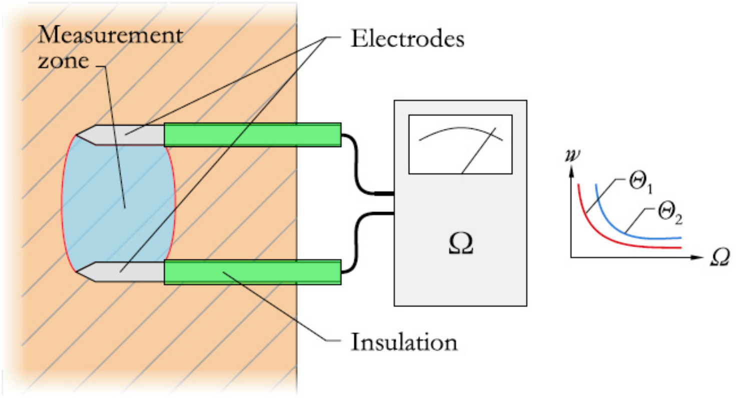


Figure 4. The resistance method (Courtesy of Palma & Steiger [13]).

3.3.2. The Capacitance Method

This method involves assessing the dielectric properties of wood, which vary with MC, using capacitance-type moisture meters equipped with surface electrodes. The electrodes are placed against the wood surface to determine the MC, with adjustments made for wood density. The shape of the electrodes can differ based on the measurement needs and the roughness of the surface, as inadequate contact can lead to inaccurate readings. This technique is suitable for estimating an average MC up to 30%, but its accuracy can be influenced by several factors, including wood density, surface moisture, the presence of wood preservatives, and the dimensions of the tested material. The main disadvantage is that the measurement is only limited to the surface of the wood. Additionally, the reading is inaccurate for rough surfaces due to bad contact and the presence of any electrolytic materials in the wood would affect the measurements. Figure 5 shows a representation of measuring the MC using the capacitance method.

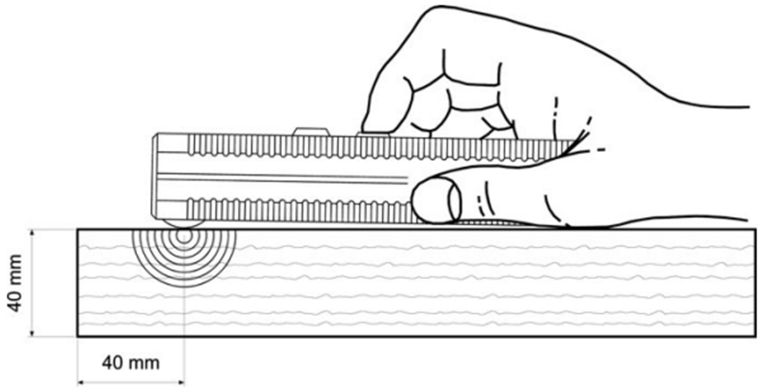


Figure 5. Representation of the capacitance method for measuring the moisture content (MC) (Courtesy of Riggio et al. [32]).

3.3.3. The Hygrometric Method

The hygrometric method estimates the MC by measuring the relative humidity (RH) of the air surrounding the wood. This is performed by placing wood samples in airtight containers or creating small boreholes in the timber, then measuring the RH and the temperature with hygrometers and thermometers until equilibrium is reached. Installation of the measurement sensors can be difficult due to the size of the sensors. Additionally, the boreholes must be sealed to limit exchange of MC between wood and air in the borehole. The MC is calculated using standard conversion charts, with adjustments made for environmental conditions and wood species. While this method is somewhat invasive and less accurate compared to direct measurement techniques, it provides a rapid MC estimation and is particularly effective for wood with high levels of extractives or soluble salts. Additionally, this method is suitable for pressure-treated wood, which exhibits high levels of electrical resistance. The main disadvantage is that the placement of the sensors can be difficult, and can affect the measured MC due to the size of sensors and transfer of MC be-tween wood and air. A comparison between results of several wood moisture meters operating on different principles of measurement can be found in [33]. Figure 6 shows the apparatus required to conduct the hygrometric method and obtain the temperature and relative humidity of the test specimen.

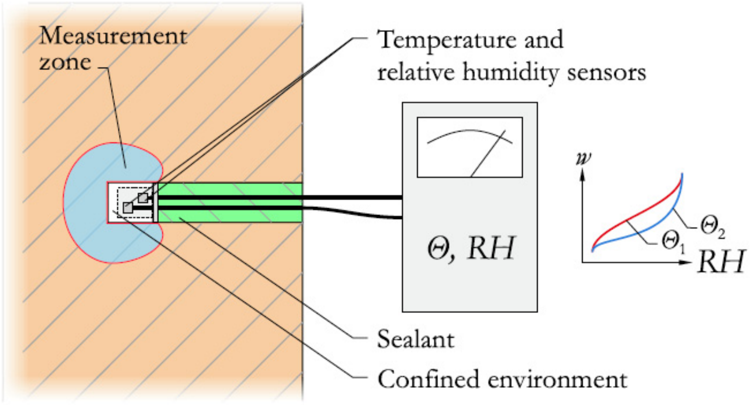


Figure 6. The hygrometric method (Courtesy of Palma & Steiger [13]).

3.4. Species Identification

Wood species identification involves determining the type of wood to evaluate its natural durability and mechanical strength. This process includes both macroscopic identifications, where visible characteristics like color, texture, and anatomical features are examined with a hand lens, and microscopic identification, which involves analyzing finer details using a microscope. The procedure typically includes cleaning the wood surface, inspecting the cross-sections, and, if needed, preparing small samples for microscopic analysis. Precise documentation of the identification methods, observed characteristics, and species information is essential. Accurate species identification is vital for ensuring the correct application of wood in structural uses and for the preservation of historical structures. More details on this procedure can be found in [32].

3.5. Assessment of the Modulus of Elasticity

Valuable information about the localized condition of structures can be obtained using nondestructive techniques for individual members. Three common methods are employed for assessing the modulus of elasticity (MOE): static bending techniques, transverse vibration techniques, and stress wave techniques [9,10,34]. The MOE measures the timber's stiffness and is determined from equations derived from the fundamental mechanics of materials, which are used to infer strength.

3.5.1. Static Bending

Static bending techniques are commonly used in nondestructive testing (NDT) of timber to assess its mechanical properties, such as stiffness and strength [9]. This relatively simple measurement involves utilizing the load–deflection relationship of a supported beam loaded at its midspan, as depicted in Figure 7. This technique is applied utilizing a machine that simulates simple beam boundary conditions. However, in situ applications can result in boundary conditions that differ from those assumed in the subsequent calculation. Therefore, the application of this method for in situ applications is limited.

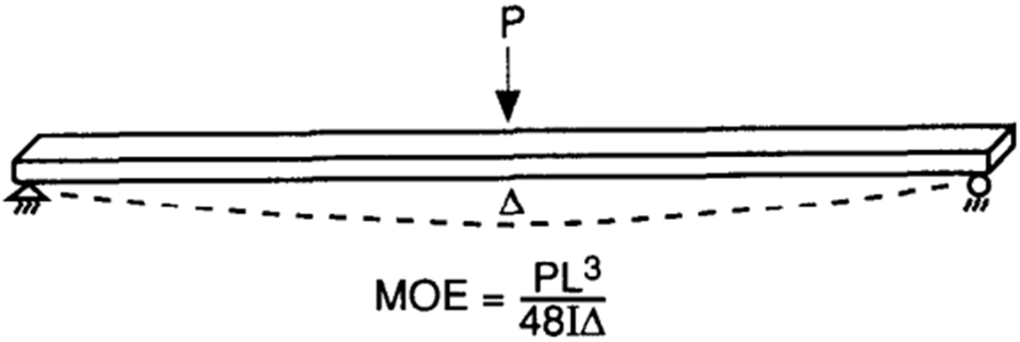


Figure 7. Static bending technique (Courtesy of Ross [9]).

3.5.2. Ambient Vibration

Ambient vibration is a technique used to assess the structural integrity and mechanical properties of wood by analyzing its natural vibration response to external disturbances. This method involves measuring the vibrations that occur when wood is subjected to ambient conditions, such as wind or minor mechanical impacts, without requiring heavy or invasive testing equipment [35]. By capturing the frequency and amplitude of these vibrations, it is possible to estimate critical properties like the MOE, which indicates the wood's stiffness and resistance to deformation. The MOE is derived from the relationship between the natural frequencies of vibration and the physical dimensions and mass of the wood, providing a reliable, non-invasive means of evaluating the wood's mechanical properties and overall quality. This approach is particularly useful for in situ assessments of buildings and bridges, allowing for ongoing measurements without causing damage or disturbance to occupants or vehicular traffic [36].

Another important use of the ambient vibration NDT technique is in bridge testing and inspections, where the purpose is to determine the dynamic properties such as frequencies and modes of the bridge using low amplitude ambient vibrations, produced by wind, or micro-tremors. Subsequently, the obtained parameters could be compared to those acquired from conducting forced vibration testing on the same bridge using a passing vehicle, such as a truck, at different speeds [35]. Figure 8 shows an example of a forced vibration test with a truck passing over a long-span bridge. Despite not requiring any actuators to excite the structure, the measured signal is usually contaminated by noise and requires special treatment to extract the modal characteristics. Additionally, this method requires a large number of sensors to accurately characterize the condition of the structure.

Figure 8. Forced vibration testing with truck passing over long span bridge (Courtesy of Horyna et al. [35]).

3.5.3. Transverse Vibration

For this NDT method, Figure 9 shows a typical configuration for a free transverse vibration test. The specimen is supported at both ends. A slight deflection is applied at the middle of the specimen, which is then allowed to oscillate freely in the vertical (transverse) direction. The oscillation frequency is measured, and the specimen's weight and dimensions are used to compute the MOE. This measurement is referred to as transverse MOE to distinguish it from static MOE [34]. It is worth mentioning that ASTM D6874-12, ref. [37], "Standard Test Methods for Nondestructive Evaluation of Wood-Based Flexural Members Using Transverse Vibration", details essential procedures for using transverse vibration NDT techniques to assess the MOE of wood materials. It is important to note that this standard recommends flatwise transverse vibration testing of lumber specimens, resulting in a low-frequency vertical vibration with fewer modes. Testing edgewise complicates the process because the specimen may vibrate in multiple modes, both vertically and horizontally, which can lead to inaccurate results. Similarly to the simple bending technique, the in situ application of this method is hindered by the ability to produce the desired boundary conditions.

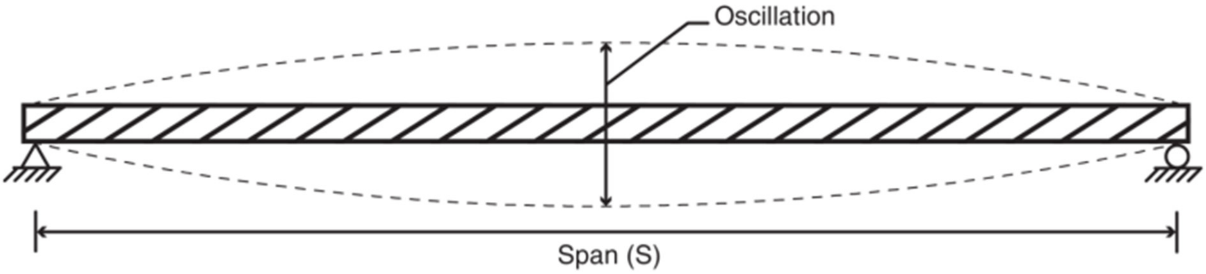


Figure 9. Typical free transverse vibration test setup (Courtesy of França et al. [34]).

3.5.4. Stress Wave

Stress wave techniques are widely used in NDT to assess the condition of timber [9,38]. These methods effectively detect internal defects, such as decay and cracks, by analyzing the propagation of stress waves through the material. These waves travel at the speed of sound through the material, reflecting from external surfaces, internal flaws, and boundaries between adjacent materials. A straightforward method of using stress waves involves measuring the time it takes for a stress wave to travel a certain distance. Given the knowledge of the material dimensions, stress wave timing can help identify decay in timber members. Decayed wood allows the stress waves to be transmitted more slowly than sound wood. We can determine its condition by measuring stress wave times along a wooden member at different locations. Longer stress wave times at specific locations indicate potential decay. Figure 10 shows the stress wave propagation schematic. The behavior of waves in sound wood greatly differs from that in decayed wood. Specifically, a stress wave attenuates more rapidly in decayed wood than in sound wood. Bozhang & Pellerin [39] observed that sound wood transmitted higher-frequency components, while decayed wood only transmitted low-frequency components, allowing them to identify incipient decay. Stress waves are commonly used to determine structural members' MOE. The velocity of the stress wave can be calculated by measuring time-of-flight measurements over a specified distance. This velocity can then be used to determine the dynamic MOE of the material and estimate various strength properties using statistical correlations [36]. Additional information regarding the different techniques that utilize stress-wave-based methods will be discussed in the following section.

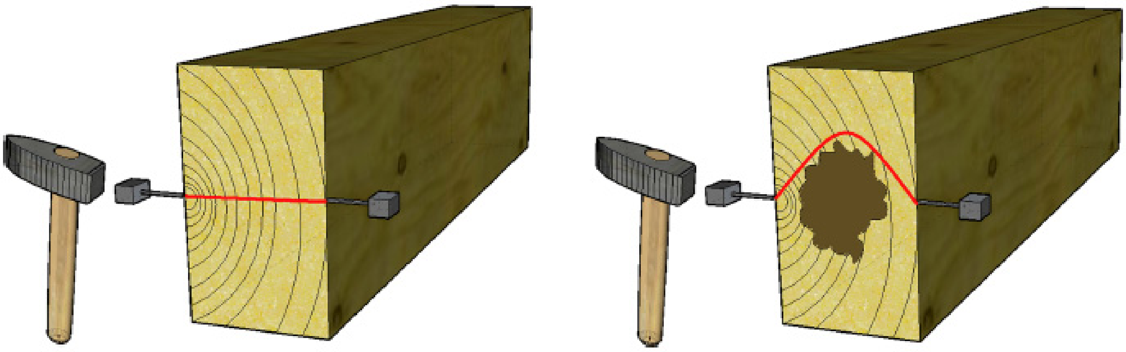


Figure 10. Stress wave propagation in sound timber (**left**) and decayed timber (**right**) (Courtesy of Dackermann et al. [38]).

3.6. Assessment of the Density of Wood

3.6.1. Drill Resistance

The drill resistance method is considered a nondestructive technique used to evaluate the density and mechanical properties of wooden structures, particularly in historical buildings [40]. This method involves using a small diameter, rotating needle to drill into the timber while recording the energy consumption required for penetration (see Figure 11). The energy consumption correlates with the wood's density; lower energy usage indicates lower density. A seismograph is a type of equipment typically used for this purpose. The needle of this equipment measures the resistance of wooden materials and converts it into the density of wooden elements. The measurements for drill resistance also indicate a significantly weakened area in the timber member [14]. This method is only limited to providing qualitative rather than quantitative information as it can report only local measurements and cannot accurately characterize the sizes of defects.

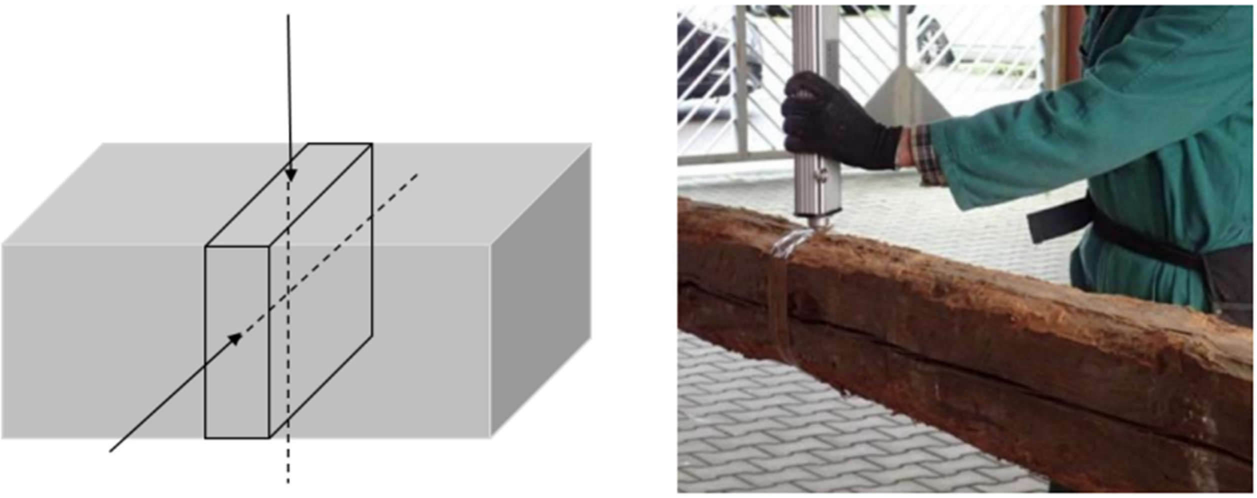


Figure 11. Drill resistance in two orthogonal directions (Courtesy of Brunetti et al. [40]).

3.6.2. Nuclear Magnetic Resonance (NMR)

Nuclear Magnetic Resonance (NMR) is a powerful analytical technique commonly used in chemistry and physics to study the molecular structure of materials. NMR can accurately measure the moisture content in wood, which is crucial for understanding wood's physical properties, decay resistance, and suitability for various applications. The technique can also map water distribution within the wood, offering insights into how water is absorbed, distributed, and desorbed, which is essential for drying processes and wood preservation. Additionally, NMR can be employed to estimate the wood density by analyzing related properties such as moisture content and porosity. However, NMR has limitations, including high costs, sensitivity challenges, and complex data interpretation. Despite these drawbacks, its unmatched ability to provide detailed, nondestructive insights makes NMR a cornerstone in research and diagnostics. More background information and details of the time-domain NMR can be found in [41].

3.6.3. Infrared Thermography

Thermographic techniques are nondestructive methods to detect internal defects and structural faults in materials, including wood and wood-based products [42]. These techniques involve capturing infrared images of the material's surface after it has been heated (active thermography) or as it cools down (passive thermography). The presence of defects, such as voids, cracks, or poor bonding, affects the material's thermal properties, causing localized temperature differences that can be detected as hot or cold spots in the thermographic images. These methods are highly effective for identifying subsurface issues in wood, such as delamination or density variations. They are particularly valuable in industrial settings where rapid, online inspection is required to ensure production quality. The ability to detect defects in real time, even in complex materials like laminated panels, makes thermography a powerful tool in quality control and evaluation. A representation of the apparatus of the infrared thermography is presented in Figure 12. On one hand, infrared thermography outperforms the other NDT methods due to the ability to conduct a non-contact inspection and cover a wide area. Additionally, it is effective for complex shapes without interrupting operations. On the other hand, this method has limitations, such as dependency on surface thermal properties, sensitivity to environmental factors, and limited penetration depth for subsurface defects. High equipment costs, the need for skilled interpretation, and calibration requirements further challenge its adoption.

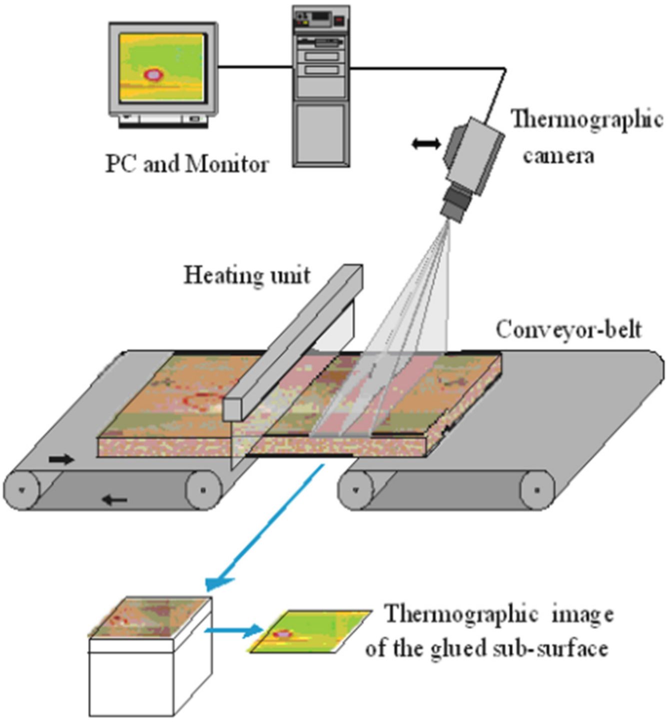


Figure 12. Schematic drawing of the thermographic setup (Courtesy of Meinlschmidt [42]).

3.6.4. Screw Withdrawal

The screw withdrawal testing method for wood involves measuring the force required to withdraw a screw from the wood, providing an indirect assessment of the wood's density, strength, and overall condition. This technique is particularly useful for evaluating the integrity of wooden structures without causing significant damage. By analyzing the resistance encountered during screw withdrawal, it is possible to infer the quality of the wood, including the presence of decay, moisture content, or other defects that might compromise its structural performance. The method is simple, practical, and straightforward, making it a valuable tool for inspectors for in situ assessments of timber, especially in applications where preserving the original structure is crucial. To that end, the density of the timber can be correlated to the withdrawal force [43]. Figure 13 shows an illustration of the use of the screw withdrawal testing.

Figure 13. Screw withdrawal force meter (Designed by Fakopp Enterprise Bt., Hungary).

Although this technique is both straightforward and cost-effective, it primarily yields localized data and may cause minor damage to the material. The results are significantly influenced by factors such as screw type, insertion depth, and material moisture content. Therefore, skilled interpretation is essential for obtaining reliable insights. Additionally, this method may not be appropriate for materials or structures where any level of damage, however minor, is deemed unacceptable.

3.6.5. Pin-Pushing

The pin-pushing nondestructive technique involves measuring the resistance encountered when a pin or small probe is pushed into the wood. This method provides insights into the wood's density, hardness, and overall structural condition. The resistance to pin pushing is closely related to the wood's density and moisture content; denser, drier wood offers greater resistance, while softer, decayed, or moisture-laden wood allows easier penetration. Pin pushing is especially useful in assessing the condition of timber in situ, as it enables the detection of internal decay or degradation with minimal impact on the wood's integrity. This technique is often used in the evaluation of historical structures, where preserving the material is critical, as well as in industrial settings where rapid assessment is needed [44]. Figure 14 portrays the use of the pin-pushing device for in situ testing and inspections. Several external factors would affect results, such as operator skill, environmental conditions, and material variability, emphasizing the need for standardized procedures and proper interpretation.

Figure 14. The pin-pushing device used for in situ testing (Courtesy of Kloiber et al. [44]).

3.7. Digital Radioscopy

Digital radioscopy is a technique used to assess the internal condition of timber structures through the use of X-rays. This method involves directing X-rays through the wood and capturing images that reveal internal features; for example, voids or decay appear lighter, while denser areas, such as metal connectors, appear darker. The process uses portable X-ray systems and necessitates strict safety protocols, including the use of dosimeters and adherence to regulatory standards. During the procedure, the X-ray source and detector are positioned on opposite sides of the timber specimen, and images are captured and analyzed for defects like decay as well as insect damage. This technique is especially valuable for structural analysis and preserving historic buildings without inflicting damage to the elements. However, it requires access to both sides of the timber and may face resolution challenges depending on the thickness of the wood and the X-ray energy used. Figure 15 illustrates a digital radioscopy setup (on the left) and a radiograph (on the right), showing details of an internal void. Beyond detecting voids and cracks, X-ray imaging can also be used for lumber grading and assessing preservative distribution.

Despite its effectiveness, the high cost of implementing this system limits its widespread use [45].

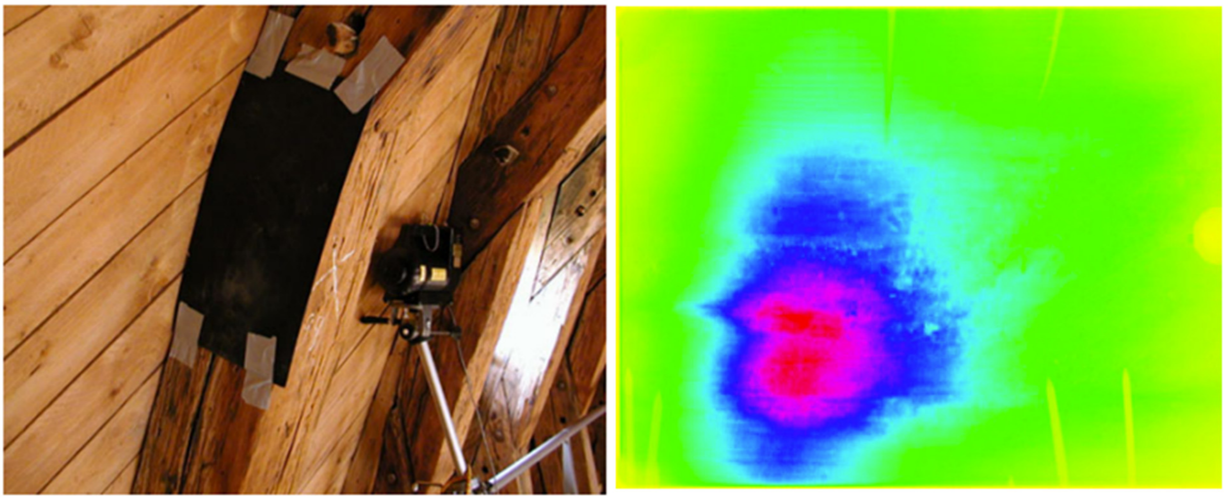


Figure 15. Setup of X-ray test (**left**) and a radiograph (**right**) showing internal defects (Courtesy of Riggio et al. [32]).

Additionally, advanced image-processing software can highlight defects, assisting in more accurate and faster evaluations. However, digital radioscopy equipment can be expensive to purchase and maintain, and it requires strict safety measures due to ionizing radiation. Moreover, the technique's effectiveness can be limited by material density or thickness, necessitating higher power sources or longer exposure times, and skilled personnel are essential for proper interpretation and operation.

3.8. Ground Penetration Radar

The Ground Penetrating Radar (GPR) is a technique used to detect defects and measure the dielectric properties of structural timber by emitting electromagnetic waves into the wood and capturing reflections from internal features such as voids, decay, or metal inclusions. Portable GPR systems can be fitted with high-frequency antennas (1.5–2.5 GHz) for high resolution with limited penetration depth or low-frequency antennas (900 MHz–1.0 GHz) for greater penetration depth with lower resolution, making them suitable for examining thick timber elements. The process involves placing the antenna on the timber surface, moving it along its length, and recording the reflections, with calibration based on known depths or using multi-offset methods. GPR is employed to identify internal defects and areas of excessive moisture content. The location of defects or intrusions is determined by calculating the wave velocity and the time measured between the emission and reception of the wave. Although GPR offers rapid and non-invasive assessment, it requires skilled interpretation for accurate data analysis and is less effective at detecting fine cracks. For a detailed explanation of the theory and application of the GPR method, please refer to [46]. An example of the interpretation of the GPR data showing several internal conditions is presented in Figure 16.

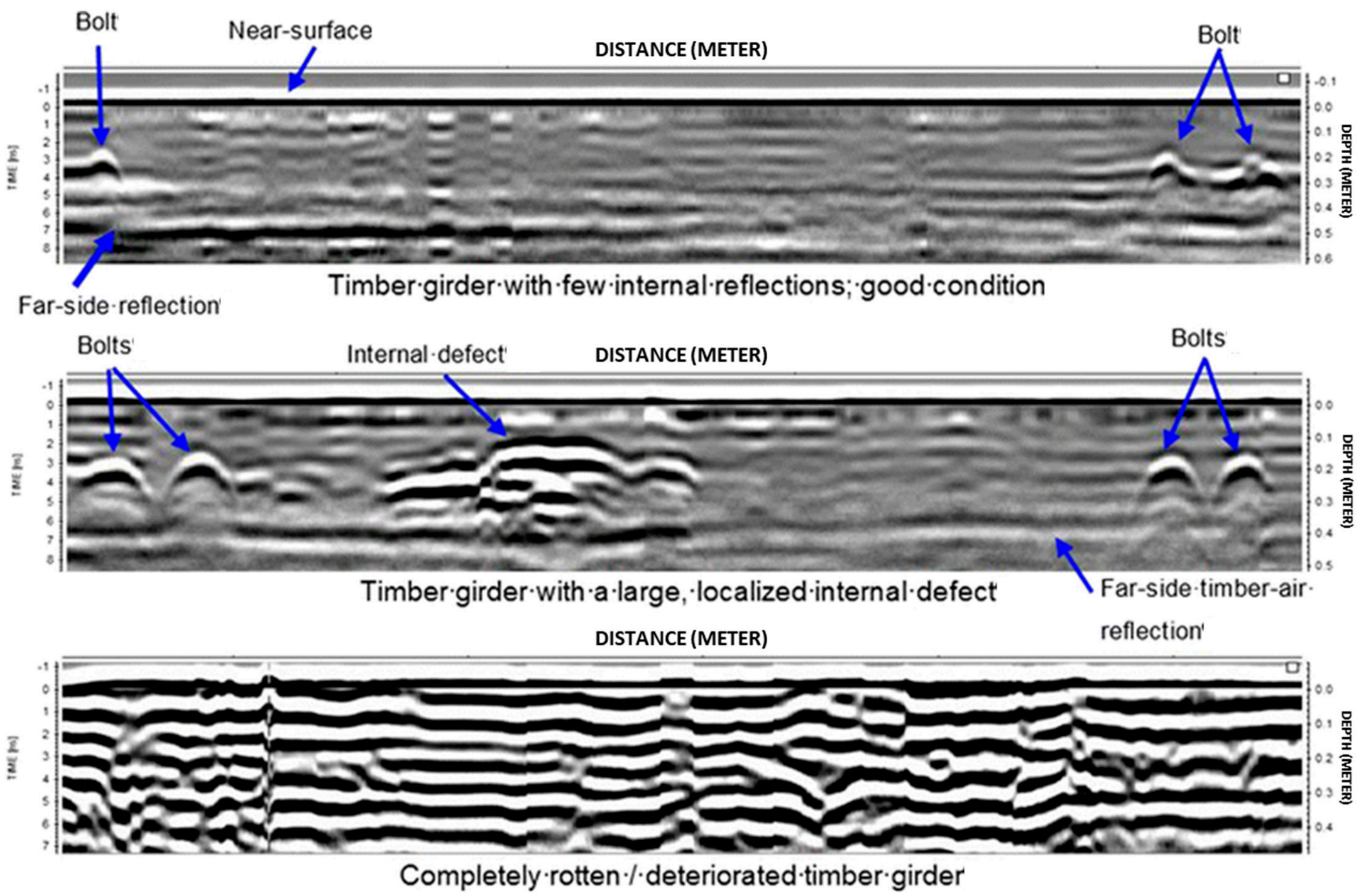


Figure 16. Example of GPR data (Courtesy of Riggio et al. [32]).

3.9. Stress Wave-Based Methods

Wave-based methods are considered local methods as they need to be applied near the defect in order to accurately identify those defects [13]. These methods are based on the propagation of waves to detect defects in the examined timber element, as internal conditions of wood elements have a substantial effect on the propagating waves. Earlier in this paper, we briefly discussed one particular application of stress-wave methods to calculate the modulus of elasticity (MOE) of wooden elements. In the following subsection, we will cover more wave-based methods that would enable inspectors to obtain a wider range of wood and timber properties during in situ testing.

3.9.1. Time-of-Flight

The time-of-flight (TOF) method is an NDT technique used to assess the internal condition of timber by measuring the time it takes for stress waves to travel through the wood. In this approach, sound waves are generated by striking the timber with an impact hammer, and sensors record the time it takes for these waves to travel between them. Healthy timber will have faster wave propagation, while slower propagation indicates deterioration, as the waves take longer to navigate around existing defects. Several factors influence TOF measurements, including the orientation of growth rings, wood species, moisture content, and temperature. The method involves performing multiple tests at different locations, especially in areas susceptible to decay, to ensure accurate results. Correct identification of wood species and consideration of environmental conditions are crucial for proper data interpretation. Overall, the TOF method is a reliable and straightforward technique that provides valuable quantitative data for maintaining and preserving timber structures [9,13,36,38,39]. Figure 17 illustrates a schematic of the different measurement modes that can be employed depending on accessibility to the wooden element.

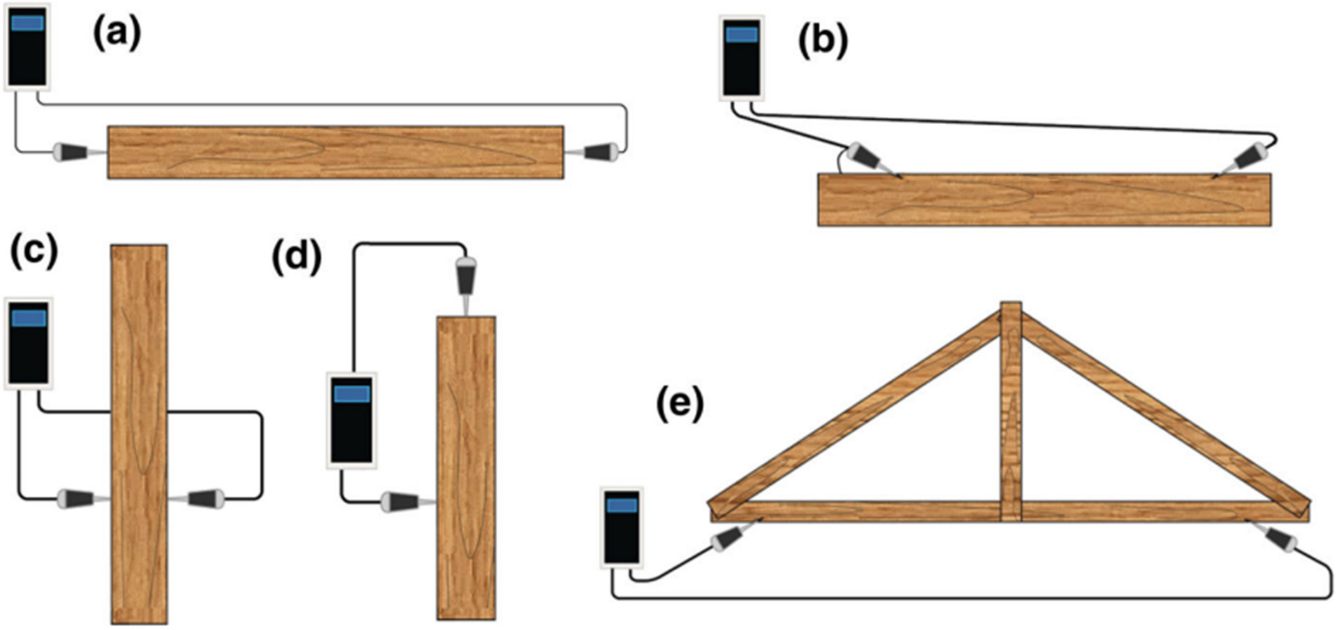


Figure 17. Schematic of various wave propagation modes (**a**) direct longitudinal, (**b**) indirect longitudinal, (**c**) transverse and (**d**) semi-direct and (**e**) indirect longitudinal transmission (Courtesy of Dackermann et al. [38]).

3.9.2. Acoustic Tomography

Sonic and ultrasonic tomography are techniques used to assess structural timber by generating cross-sectional images based on the propagation of stress waves. These methods involve measuring the TOF of stress waves using sensors attached around the timber's surface, which are then used to create velocity distributions that reveal internal defects such as knots, cracks, and decay. The necessary equipment includes sensors, an oscilloscope, a function generator, a timer, signal amplifiers and filters, hammers for low-frequency waves, or transducers for high-frequency waves, and portable computers. The procedure involves generating stress waves, collecting TOF data, calculating wave velocities, and reconstructing tomographic images. Areas with high velocity indicate sound timber, while areas with low velocity suggest the presence of defects. Although this method enables large-scale, non-invasive evaluation, its resolution depends on the signal's frequency and wavelength, providing primarily qualitative analysis. Consequently, it often needs to be supplemented with additional techniques for a more detailed investigation of identified areas. It is worth noting that this technique can be costly and complex, requiring multiple sensors, specialized software, and skilled interpretation to avoid misreading artifacts or noise. To illustrate, Figure 18 shows a setup for stress wave tomography testing on a timber column on the left, and the corresponding tomogram on the right, showing wave speeds between sensor pairs, allowing for the identification of the column's internal condition. More details about the applications and limitations of this method can be found in [13,47,48].

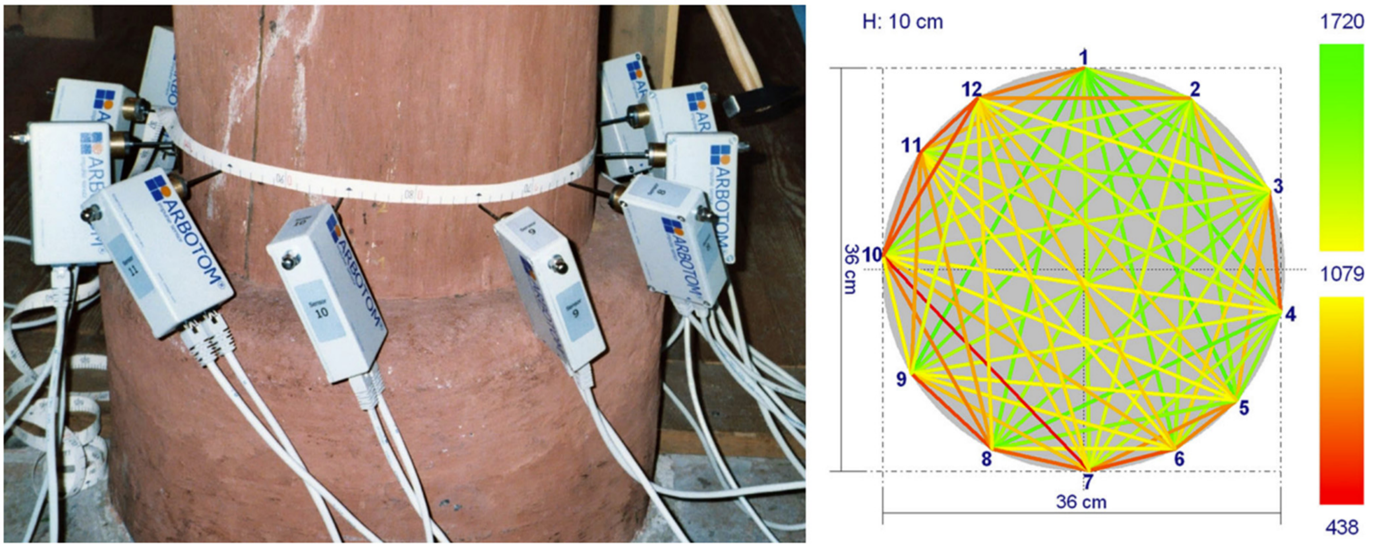


Figure 18. Setup of stress wave tomography technique (on the **left**) and the corresponding tomograph (on the **right**) (Courtesy of Dackermann et al. [38]).

3.9.3. Ultrasonic Echo

The ultrasonic echo method evaluates the internal condition of timber elements by examining the reflections of ultrasonic stress waves, both longitudinal and transverse. These waves reflect off surfaces where there are changes in material, such as the back surface of the wood or any internal defects. Due to natural wood's low density, high-intensity, low-frequency probes (in the range of 50 kHz to 200 kHz) are typically used, with low-frequency shear waves being particularly effective because they experience minimal signal attenuation, even though their larger wavelength limits the size of detectable defects. The sensor head, often equipped with multiple sensors, is placed on just one side of the timber being inspected, and the waves are reflected back to these sensors. Internal defects are indicated by alterations in the reflected echo signal. The results are displayed as A-scans, which show the reflected energy over time, and B-scans, which combine A-scans to provide a two-dimensional cross-sectional view. By combining B-scans, C-scans can be produced, offering three-dimensional structural information. While this technique allows for the direct detection of changes like back walls or internal damage, precisely locating the exact position of damage within the specimen can be challenging. The method shows promise for in situ timber assessments but requires expertise due to the complexity of influencing factors, and accurately defining internal defects based solely on the reflected wave results remains difficult. Additionally, highly attenuating or very thick materials can reduce signal clarity and penetration, and advanced ultrasonic equipment (like phased-array systems) can be expensive. A sample scan on a wooden specimen using the ultrasonic echo method is portrayed in Figure 19. More details about this technique can be found in [49].

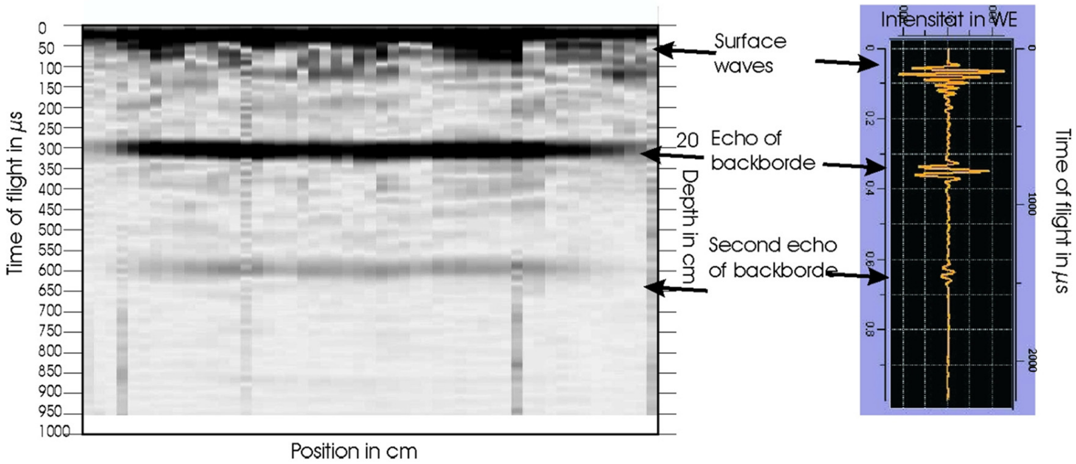


Figure 19. Results of an ultrasonic echo scan on a specimen (Courtesy of Hasenstab et al. [49]).

3.9.4. Acoustic Emission

Acoustic Emission (AE) refers to the release of transient elastic waves within a material when it experiences localized, irreversible changes such as cracking, deformation, or stress-induced damage. These waves are generated by the sudden release of strain energy and can propagate through the material. AE is a nondestructive evaluation (NDE) technique widely used for real-time monitoring of structural integrity and detecting micro-level events before visible damage occurs. In wood and timber structures, AE is particularly useful for monitoring processes like drying, machining, and fracture progression, as well as identifying biological activities such as termite infestation. The process begins with the setup of piezoelectric sensors that convert mechanical vibrations into electrical signals. These sensors are strategically placed on the material and coupled with a suitable agent to ensure efficient signal transmission as shown in Figure 20. During monitoring, AE signals are naturally generated by stress events or induced artificially through methods like pencil lead break tests for calibration. The detected signals are processed in real-time using amplifiers, filters, and data acquisition systems to extract key parameters like amplitude, energy, and frequency. The method's sensitivity to material properties, such as anisotropy and moisture content, makes it a valuable tool for understanding the behavior of wood and ensuring structural health, though it requires advanced signal processing and interpretation due to challenges like wave attenuation and noise interference. Nasir et al. [50] present a detailed review of this method.

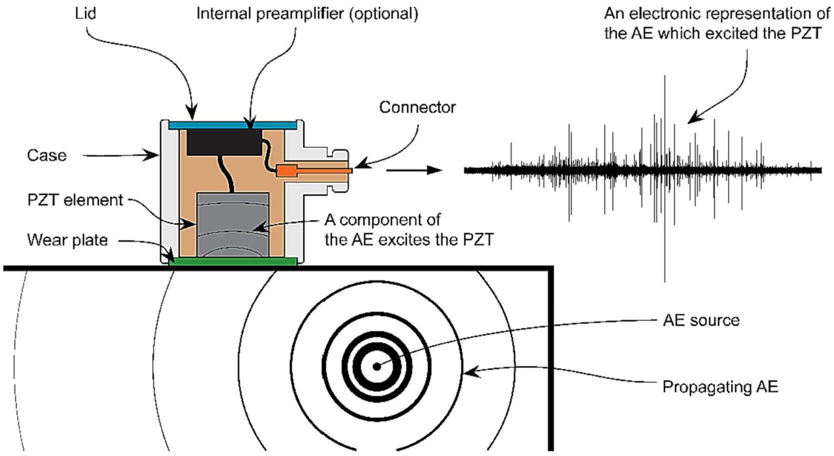


Figure 20. An illustration of a piezoelectric transducer (PZT) used to acquire the AE signal and convert it to an electrical signal (Courtesy of Unnþórsson [51]).

3.10. Correlation Between Mechanical and NDT Parameters

The relationship between mechanical parameters, such as tensile strength, hardness, fatigue resistance, and fracture toughness, and NDT techniques is crucial for evaluating material performance without causing damage. NDT methods provide indirect measurements of material properties that can often be correlated with mechanical behavior.

For instance, Berkovits and Fang [52], concluded that Acoustic Emission (AE) is an excellent tool to define initiation, and that the stress intensity factor threshold can be determined through AE, with comparable results. Eddy current testing assesses electrical conductivity, which correlates with material hardness and microstructure variations [53]. Ultrasonic testing of concrete is a confirmed method for quality assessment, uniformity, and crack depth estimation in concrete. The test procedure has been standardized as the "Standard Test Method for Pulse Velocity through Concrete" [54].

For timber sections and members, Josifovski et al. [11] recently developed an NDT method based on relating the resistance to bending of timber beams to the parameters of nondestructive methods. The proposed method uses X-rays and ultrasonic waves to provide a preliminary examination of the specimen and serves as a baseline for relating the NDT parameters to mechanical parameters. Then, mechanical tests for compression and bending are performed to develop a relationship between both sets of parameters. The in situ assessment proved the validity of the method and the effectiveness of relating mechanical and NDT parameters. More details about the technique and its applications can be found in [11].

As a final note, these procedures should be adapted to the specific characteristics of the tested materials. This can be achieved by conducting destructive testing on laboratory specimens to develop tailored correlation curves, linking the quantities measured directly by NDT devices with their corresponding mechanical properties. Such customization ensures that the peculiarities of the material, such as anisotropy or heterogeneity, are appropriately accounted for. Additionally, effective strategies to assess the deterioration rate of materials using nondestructive tests repeated over time would be invaluable. This can be facilitated by calibrating NDT techniques on specimens subjected to controlled aging in laboratory conditions, thereby simulating real-world deterioration processes. Such advancements would enhance the predictive capabilities of NDTs and their reliability for long-term material health monitoring.

4. Summary of NDT Methods Applicable to Timber Structures

This section aims to group the previously discussed NDT methods into one flowchart for easier visualization and selection of available techniques (Figure 21). As such, future inspectors of buildings and bridges can decide on the NDT method to be used (or combine several methods) based on the inspection context, applicable conditions, and constraints at the time of the assessment.

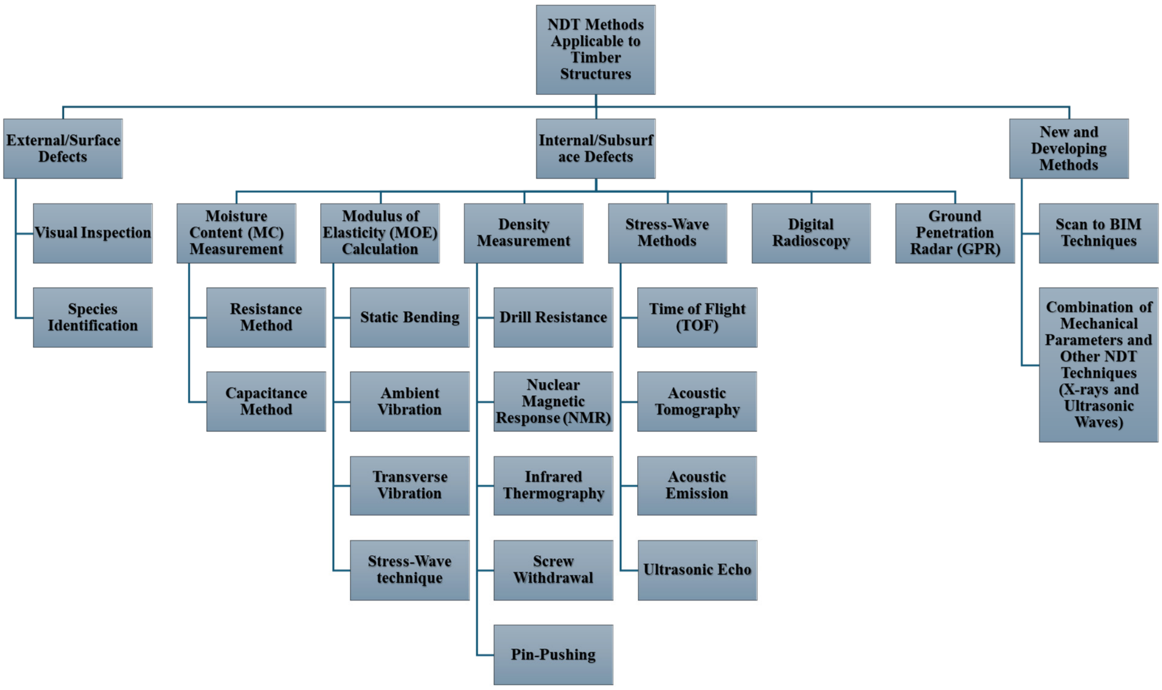


Figure 21. Flowchart summarizing all applicable NDT methods to timber structures.

5. Case Studies on the Application of NDT Methods to Timber Structures

This section will discuss two case studies where NDT methods were applied to timber structures:

a. NDT assessment of Villa Ivonne, Meliana, Spain
   Villa Ivonne is a traditional building located in Meliana near Valencia, Spain. Currently, the historical building suffers from significant structural damage, including wood rot, biological infestations, and water leaks. Researchers from the Polytechnic University of Valencia conducted a comprehensive assessment of the timber structure using NDT methods [55]. The evaluation combined visual inspections with ultrasonic and micro-drilling devices to detect internal defects and assess the timber quality.
   Visual inspection determined the timber species as Pinus sylvestris and identified areas of damage and biological decay. Ultrasonic testing assessed the timber's dynamic modulus of elasticity, revealing poor quality. Micro-drilling further identified discontinuities at the upper surface of roof rafters and areas in contact with wall materials, indicative of wood rot.
   The used NDT methods effectively diagnosed the timber condition with minimal invasiveness. This led to recommendations to repair damaged ends and broken elements by means of epoxy resins and fiberglass bars or, eventually, substitution of broken elements by new elements of the same wood species.
b. NDT assessment of Umatilla County Timber Bridges, Oregon, USA
   NDT assessments were conducted on two rural bridges, which were identified as being deficient, in Umatilla County, Oregon. Following the NDT assessments, the bridges were removed and taken to the Wood Materials and Engineering Laboratory at WSU for verification of NDT results [56].
   For the first bridge, decay was identified by visual inspection of stinger ends due to water exposure. This decay was confirmed by stress wave tests, which were then validated by laboratory tests.
   Visual inspection of the second bridge indicated that it is in good shape except for some of the columns, which had visual signs of decay. The stress wave tests proved

that the decking was in excellent shape; however, it showed that all the columns had signs of decay in the columns.

The decking and columns were then evaluated in the laboratory using destructive and nondestructive methods. The results closely matched the NDT field results.

These case studies collectively demonstrate the efficacy and versatility of nondestructive evaluation (NDE) techniques in diagnosing decay, evaluating structural integrity, and planning targeted repairs for timber structures. This ensures the safety and longevity of both historic and functional timber constructions.

6. Conclusions

This research paper presented a review of nondestructive testing techniques currently being used for the evaluation of timber structures in buildings and bridges. This paper also emphasized the significance of using NDT methods in maintaining the structural integrity of wooden structural elements without damaging the materials. These techniques are essential for assessing the condition of timber in existing structures, as they enable the detection of issues like decay, rot, and insect infestations without resorting to invasive measures.

This review paper encompassed a variety of NDT methods, such as visual inspection, stress wave timing, ultrasonic testing, radiography, and infrared thermography, among others. Each of these techniques has its specific applications and limitations. Visual inspection, though the most fundamental, is effective in spotting surface defects and general wear. More advanced methods like stress wave and ultrasonic testing allow inspectors to identify internal flaws and evaluate the mechanical properties of timber. Radiography is particularly valuable for uncovering hidden defects, while infrared thermography can detect moisture or heat irregularities that may signal underlying issues.

Furthermore, this review paper highlights the importance of carefully selecting the right NDT method depending on the specific context in which it will be used by the inspector, including the type of structure, the timber's condition, and the level of detail required. It is often advisable to combine multiple NDT techniques to enhance the assessment's accuracy and reliability. Last but not least, these nondestructive techniques are crucial tools for inspectors of buildings and bridges, ensuring the safety, durability, and sustainability of timber structures.

Author Contributions: Conceptualization, Z.A.; methodology, H.A.S., O.M. and M.E.; software, Z.A.; formal analysis, Z.A.; investigation, H.A.S., O.M. and M.E.; resources, H.A.S., O.M. and M.E.; data curation, Z.A.; writing—original draft preparation, H.A.S., O.M. and M.E.; writing—review and editing, Z.A.; visualization, Z.A.; supervision, Z.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Aghayere, A.; Vigil, J. *Structural Wood Design ASD/LRFD*, 2nd ed.; CRC Press: Boca Raton, FL, USA; Taylor & Francis Group: Abingdon, UK, 2017.
2. Breyer, D.E.; Fridley, K.J.; Cobeen, K.E.; Pollock, D.G., Jr. *Design of Wood Structures—ASD/LRFD*; McGraw-Hill: New York, NY, USA, 2007.

3. Seavey, R.; Larson, T. *Inspection of Timber Bridges 2002–34 Final Report*; Minnesota Department of Transportation, Office of Research Services: St. Paul, MN, USA, 2002. Available online: http://www.lrrb.org/pdf/200234.pdf (accessed on 15 August 2024).
4. Ross, R.J.; Pellerin, R.F.; Volny, N.; Salsig, W.W.; Falk, R.H. *Inspection of Timber Bridges Using Stress Wave Timing Nondestructive Evaluation Tools A Guide for Use and Interpretation*; US Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 1999.
5. Brashaw, B.; Wacker, J.; Ross, R.J. *Advanced Timber Bridge Inspection—Field Manual for Inspection of Minnesota Timber Bridges*; University of Minnesota and Minnesota Department of Transportation: Minneapolis, MN, USA, 2014.
6. Zielińska, M.; Rucka, M. Non-destructive Testing of Wooden Elements. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1203*, 032058. [CrossRef]
7. Firestone, F.A. The Supersonic Reflectoscope: An Instrument for Inspecting the Interior of Solid Parts by Means of Sound Waves. *J. Acoust. Soc. Am.* **1946**, *17*, 287–299. [CrossRef]
8. Hellier, C. *Handbook of Nondestructive Evaluation*; McGraw-Hill: New York, NY, USA, 2012.
9. Ross, R.J.; Pellerin, R.F. Review of Nondestructive Evaluation of Timber. In Proceedings of the Technical Aspects of Maintaining, Repairing Preserving Historically Significant Ships, Charleston, MA, USA, 12–14 September 1994; pp. 78–91.
10. Ross, R.J.; Pellerin, R.F. *Nondestructive Testing for Assessing Wood Members in Structures: A Review*; General Technical Report FPL; GTR-70):39 p.: Ill.; 28 Cm; U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 1994. [CrossRef]
11. Josifovski, A.; Todorović, N.; Milošević, J.; Veizović, M.; Pantelić, F.; Aškrabić, M.; Vasov, M.; Rajčić, A. An Approach to In Situ Evaluation of Timber Structures Based on Equalization of Non-Destructive and Mechanical Test Parameters. *Buildings* **2023**, *13*, 1405. [CrossRef]
12. Llana, D.F.; Iniguez-Gonzalez, G.; Diez, M.R.; Arriaga, F. Nondestructive testing used on timber in Spain: A literature review. *Competitiveness* **2020**, *22*, 133–156. [CrossRef]
13. Palma, P.; Steiger, R. Structural health monitoring of timber structures—Review of available methods and case studies. *Constr. Build. Mater.* **2020**, *248*, 118528. [CrossRef]
14. Pahnabi, N.; Schumacher, T.; Sinha, A. Imaging of Structural Timber Based on In Situ Radar and Ultrasonic Wave Measurements: A Review of the State-of-the-Art. *Sensors* **2024**, *24*, 2901. [CrossRef] [PubMed]
15. Hudson, O.; Goubard, M.; Langenberg, S.; Ford, S. *Non-Destructive Testing of Timber Trending Stories Sustainable Challenges in the Cement Industry Discussing Construction Heritage and Preservation with Dr. Silke Langenberg Providing Emergency Accommodation with Modular Shelters*; AZOBuild: Sydney, Australia, 2022. Available online: https://www.azobuild.com/article.aspx?ArticleID=8474 (accessed on 20 August 2024).
16. Bagheri, S.; Tabiatnejad, D. Optimum Selection of Yield Displacement of Metallic-Yielding Dampers in Steel Moment Resisting Frames. *Sharif J. Civ. Eng.* **2016**, *31*, 71–78.
17. Mehrabi, A.; Tabiatnejad, D.; Dolati, S.S.K. Connection Systems and Methods for Skewed Frames. U.S. Patent 11,746,484 B1, 5 September 2023.
18. Mehrabi, A.; Farhangdoust, S.; Dolati, S.S.K.; Tabiatnejad, D. *Epoxy Dowel Pile Splice Evaluation*; Department of Transportation, Research Center: Washington, DC, USA, 2022. Available online: https://rosap.ntl.bts.gov/view/dot/66069 (accessed on 20 August 2024).
19. Tabiatnejad, D.; Dolati, S.S.K.; Mehrabi, A.; Helwig, T.A. Fatigue Consideration for Tension Flange over Intermediate Support in Skewed Continuous Steel I-Girder Bridges. *Infrastructures* **2024**, *9*, 99. [CrossRef]
20. Tabiatnejad, D.; Tabiatnejad, B.; Dolati, S.S.K.; Mehrabi, A. Damage Detection in External Tendons of Post-Tensioned Bridges. *Infrastructures* **2024**, *9*, 103. [CrossRef]
21. Jayne, B.A. Vibrational properties of wood as indices of quality. *For. Prod. J.* **1959**, *9*, 413–416.
22. Dolati, S.S.K.; Caluk, N.; Mehrabi, A.; Dolati, S.S.K. Non-destructive testing applications for steel bridges. *Appl. Sci.* **2021**, *11*, 9757. [CrossRef]
23. Dolati, S.S.K.; Malla, P.; Ortiz, J.D.; Mehrabi, A.; Nanni, A. Identifying NDT methods for damage detection in concrete elements reinforced or strengthened with FRP. *Eng. Struct.* **2023**, *287*, 116155. [CrossRef]
24. Dolati, S.S.K.; Malla, P.; Ortiz, J.; Mehrabi, A.; Nanni, A. Nondestructive Testing Applications for FRP Reinforced or Strengthened Concrete Elements. *Struct. Congr.* **2023**, *2023*, 217–229.
25. Farhangdoust, S.; Mehrabi, A. Health Monitoring of Closure Joints in Accelerated Bridge Construction: A Review of Non-Destructive Testing Application. *J. Adv. Concr. Technol.* **2019**, *17*, 381–404. [CrossRef]
26. Feghhi, M.; Dolati, S.S.K.; Mehrabi, A.; Malla, P.; Tabiatnejad, D. A Framework for Condition and Risk Assessment for Sustainable Management of PT Bridges. *Sustainability* **2024**, *16*, 9703. [CrossRef]
27. Malla, P.; Dolati, S.S.K.; Ortiz, J.D.; Mehrabi, A.B.; Nanni, A.; Ding, J. Damage Detection in FRP-Reinforced Concrete Elements. *Materials* **2024**, *17*, 1171. [CrossRef] [PubMed]

28. Malla, P.; Khedmatgozar Dolati, S.S.; Ortiz, J.D.; Mehrabi, A.B.; Nanni, A.; Dinh, K. Feasibility of Conventional Non-Destructive Testing Methods in Detecting Embedded FRP Reinforcements. *Appl. Sci.* **2023**, *13*, 4399. [CrossRef]
29. Mehrabi, A.; Nanni, A.; Saman, S.; Dolati, K.; Polanco, J.O. *A Framework for Field Inspection of In-Service FRP Reinforced/Strengthened Concrete Bridge Elements*; Florida International University: Miami, FL, USA, 2024. Available online: https://digitalcommons.fiu.edu/cee_fac/9 (accessed on 20 August 2024).
30. Ortiz, J.D.; Dolati, S.S.K.; Malla, P.; Mehrabi, A.; Nanni, A. Nondestructive Testing (NDT) for Damage Detection in Concrete Elements with Externally Bonded Fiber-Reinforced Polymer. *Buildings* **2024**, *14*, 246. [CrossRef]
31. Liu, J.; Xu, D.; Hyyppä, J.; Liang, Y. A survey of applications with combined BIM and 3D laser scanning in the life cycle of buildings. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2021**, *14*, 5627–5637. [CrossRef]
32. Riggio, M.; Anthony, R.W.; Augelli, F.; Kasal, B.; Lechner, T.; Muller, W.; Tannert, T. In situ assessment of structural timber using non-destructive techniques. *Mater. Struct.* **2014**, *47*, 749–766. [CrossRef]
33. Běťák, A.; Zach, J.; Misák, P.; Vaněrek, J. Comparison of Wood Moisture Meters Operating on Different Principles of Measurement. *Buildings* **2023**, *13*, 531. [CrossRef]
34. França, F.J.; Seale, R.D.; Ross, R.J.; Shmulsky, R.; França, T.S.A. *Using Transverse Vibration Nondestructive Testing Techniques to Estimate Stiffness and Strength of Southern Pine Lumber*; Research Paper FPL-RP-695; US Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 2018; 8 p., 695.
35. Horyna, T.; Foschi, R.O.; Ventura, C.E. Response of timber bridge to traffic loading. *J. Bridge Eng.* **2001**, *6*, 69–77. [CrossRef]
36. Emerson, R.N.; Pollock, D.G.; Kainz, J.A.; Fridley, K.J.; Mclean, D.; Ross, R.J. Nondestructive Evaluation Techniques for Timber Bridges. In Proceedings of the 5th World Conference on Timber Engineering, Montreaux, Switzerland, 17–20 August 1998; Presses Polytechniques et Universitaires Romandes: Lausanne, Switzerland, 1999. Available online: https://www.ndt.net/article/v04n11/emerson/emerson.htm (accessed on 21 August 2024).
37. *ASTM Standard D6874-12, 2020*; Standard Test Methods for Nondestructive Evaluation of Wood-Based Flexural Members Using Transverse Vibration. ASTM International: West Conshohocken, PA, USA, 2020. Available online: https://www.astm.org/d6874-12.html (accessed on 21 August 2024).
38. Dackermann, U.; Crews, K.; Kasal, B.; Li, J.; Riggio, M.; Rinn, F.; Tannert, T. In situ assessment of structural timber using stress-wave measurements. *Mater. Struct.* **2014**, *47*, 787–803. [CrossRef]
39. Bozhang, S.; Pellerin, R.F. Nondestructive evaluation of the degree of deterioration in wood: Stress wave frequency spectrum analysis. In Proceedings of the NDT 1996: 10th International Symposium on Nondestructive Testing of Wood, Lausanne, Switzerland, 26–28 August 1996; pp. 99–115.
40. Brunetti, M.; Aminti, G.; Vicario, M.; Nocetti, M. Density Estimation by Drilling Resistance Technique to Determine the Dynamic Modulus of Elasticity of Wooden Members in Historic Structures. *Forests* **2023**, *14*, 1107. [CrossRef]
41. Li, J.; Ma, E. Characterization of water in wood by time-domain nuclear magnetic resonance spectroscopy (Td-nmr): A review. *Forests* **2021**, *12*, 886. [CrossRef]
42. Meinlschmidt, P. Thermographic detection of defects in wood and wood-based materials. In Proceedings of the 14th International Symposium of Nondestructive Testing of Wood, Hannover, Germany, 2–4 May 2005.
43. Íñiguez-González, G.; Montón, J.; Arriaga, F.; Segués, E. In-Situ Assessment of Structural Timber Density Using Non-Destructive and Semi-Destructive Testing. *BioResources* **2015**, *10*, 2256–2265. [CrossRef]
44. Kloiber, M.; Drdácký, M.; Machado, J.S.; Piazza, M.; Yamaguchi, N. Prediction of mechanical properties by means of semi-destructive methods: A review. *Constr. Build. Mater.* **2015**, *101*, 1215–1234. [CrossRef]
45. Zombori, B. "In situ" Nondestructive Testing of Built in Wooden Members. *NDT. Net* **2001**, *6*, 1–9.
46. Jol, H.M. *Ground Penetrating Radar Theory and Applications*; Elsevier: Amsterdam, The Netherlands, 2009.
47. Riggio, M.; Piazza, M. Acoustic tomography of timber elements. In Proceedings of the International Conference on Structural Health Assessment of Timber Structures (SHATIS), Lisbon, Portugal, 16–17 June 2011; Dolnośląskie Wydawnictwo Edukacyjne: Wrocław, Poland, 2011.
48. Riggio, M.P.; Piazza, M. Stress waves tomography for the analysis of structural timber: Limits, applications, possible combinations with other analysis techniques. In Proceedings of the 17th International Nondestructive Testing and Evaluation of Wood Symposium, Sopron, Hungary, 14–16 September 2011; pp. 611–616.
49. Hasenstab, A.; Krause, M.; Osterloh, K. Testing of wooden construction elements with ultrasonic echo technique and X-ray. In Proceedings of the 9th European Conference on Non-Destructive Testing, Berlin, Germany, 25–29 September 2006; pp. 25–29.
50. Nasir, V.; Ayanleye, S.; Kazemirad, S.; Sassani, F.; Adamopoulos, S. Acoustic emission monitoring of wood materials and timber structures: A critical review. *Constr. Build. Mater.* **2022**, *350*, 128877. [CrossRef]
51. Unnþórsson, R. Hit detection and determination in AE bursts. In *Acoustic Emission-Research and Applications*; InTech: Rijeka, Croatia, 2013; pp. 1–20. [CrossRef]
52. Berkovits, A.; Fang, D. Study of fatigue crack characteristics by acoustic emission. *Eng. Fract. Mech.* **1995**, *51*, 401–416. [CrossRef]

53. Khan, S.H.; Khan, A.N. Metallurgical Characterization of Bainitic Steel by Eddy Current Method. *J. Fail. Anal. Prev.* **2016**, *16*, 1121–1125. [CrossRef]
54. *ASTM Standard C597-22, 2016*; Standard Test Method for Ultrasonic Pulse Velocity Through Concrete. ASTM International: West Conshohocken, PA, USA, 2023. Available online: https://www.astm.org/c0597-22.html (accessed on 23 August 2024).
55. Palaia, L.; Tormo, S.; López, V.; Monfort, J. NDT assessment of timber structures: A case study–Villa Ivonne, Meliana. *WIT Trans. Built Environ.* **2011**, *118*, 529–540.
56. Pellerin, R.F.; Lavinder, J.A.; Ross, R.J.; Falk, R.H. Nondestructive Evaluation of Timber Bridges. In *Nondestructive Evaluation of Materials and Composites*; SPIE: Scottsdale, AR, USA, 1996; pp. 275–284. Available online: https://www.fpl.fs.usda.gov/documnts/pdf1996/pelle96b.pdf (accessed on 23 August 2024).