Recommendation of RILEM TC 215-AST: In-situ assessment of structural timber using Stress Wave Measurements

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Abstract:

This paper summarizes the test recommendations for in-situ assessment of structural timber using stress wave measurements as developed by the RILEM Technical Committee AST 215 "In-situ assessment of structural timber". In the first part, the basic principles, the equipment, and the practical application of stress-wave-based testing using the time-of-flight method are described. A detailed testing procedure provides hands-on information on the execution of in-field stress wave testing. A typical example is given to demonstrate step-by-step on how to evaluate stress wave readings and the health state of the inspected timber member. The latter part of the paper gives a short overview of the use of acoustic tomography and ultrasonic echo methods.

1. Introduction

Methods for assessing the condition of timber structural elements can be non-destructive (NDT), semi-destructive (SDT) or destructive. NDT techniques are useful for rapid screening of structural members and searching for defective areas and are generally based on correlations between non-destructive and destructive parameters. The RILEM Technical Committee AST 215 “In-situ assessment of structural timber” has developed recommendations for the use of several NDT [1] and SDT [2]. This paper summarizes the recommendation for in-situ assessment of structural timber using stress wave measurements. Specifically, following techniques are considered: time-of-flight methods (chapter 2), sonic/ultrasonic tomography (chapter 3), and ultrasonic echo methods (chapter 4).

2. Time-of-flight method

2.1 Basics

Changes in the mechanical and physical properties of timber have a direct effect on the way sound travels through the material. This principle is the basis of one of the oldest and still most widely used techniques to detect interior deterioration in trees, wood, and timber structures. Creating sound waves in timber by hitting the surface with an object (typically a hammer) can reveal defects such as decay and interior voids. Changes in the tone of the sound resulting from the impact indicate different properties of the wood and can be discerned by individuals with a moderate level of experience. While this method is fast and simple to conduct, it can only reveal extensive defects and does not provide any quantitative measure. It is also highly subjective; diagnosis can vary between inspectors.

To provide a quantitative measure on the travel of sound in timber, different non-destructive testing (NDT) methods have been developed that record and analyze the propagation of sound waves. One of the most common and simplest techniques for the detection of internal voids and deterioration in timber is to measure the time-of-flight of sound waves.

Typically, a sound wave, also called a stress wave, is induced by striking one side of the inspected specimen with an impact hammer, which is instrumented with a sensor (such as an accelerometer or force sensor), or a normal hammer with a separate sensor that is located at the impact site. At the time of the impact, the sensor emits a start signal to a timer. When the propagating stress wave reaches the opposite side of the timber specimen, an additional sensor, which is mounted directly opposite to the side of the impact location, senses the arrival of the stress wave and sends a stop signal to the timer. From the measured times and the known distance between the impact location and the second sensor, the velocity of the wave can be calculated and used to assess the internal physical conditions.

Generally, stress waves propagate quickly through dense, solid materials, while voids, cracks, or decay attenuate and divert stress waves since the waves must find a path around the defects resulting in increased transmission times. Hence, fast moving stress wave indicates sound and/or high quality timber, while slow wave propagation suggests deteriorated and/or low quality timber. This concept is illustrated in Figure 1.

The ability to detect and locate damage depends in general on the size of the defect and the level of deterioration. Usually, early stages of decay cannot be detected [3]. Also, the type of damage is important; for damage due to decay fungi, for example, success of the technique depends upon the type of fungi present; brown rots are generally more easily detected than white rots [4,5].

Further, since timber is a naturally grown, inhomogeneous material consisting of long, tubular cells arranged in rings, the propagation of stress waves in timber is affected by various factors including the wood species, the moisture content (MC), and the orientation of growth rings relative to the direction of the impact. In stress-wave-based timber evaluation, the timber specimen is either excited from one end or a side of the specimen. When the impact is imparted at the end face of a timber member, then a primarily longitudinal stress wave along the length of the cell structure is generated (Figure 2left). Hammering a side of a timber member will generate a wave across the cross-section in transverse direction to the timber cells (Figure 2 right). Since stress waves travel the entire span of the member, a longitudinal impact gives the averaged global stress wave velocity along the full length of the specimen. Transverse waves, however, travel only over a localized portion of the specimen and present only local properties of the timber member.

For sound wood, the longitudinal stress wave velocities generally range between 3500 m/s and 5000 m/s, while the velocity of transverse stress waves falls in the range of 1000 m/s to 1500 m/s. Since longitudinal stress waves travel along the vertically oriented cells with only a few or no boundaries to pass, they have a higher velocity, while transverse waves encounter numerous interfaces and boundaries at the cell walls and travel with slower velocity. On average, the speed of sound across the grain is about one-fifth to one-third of the longitudinal value [6-8]. For sound wood, the stress wave velocities for longitudinal (parallel to the grain) and radial (perpendicular to the grain) orientations are listed for various wood species in Table 1. These reference velocities can be used to evaluate the measured wave velocity and assess the internal condition of the timber specimen. The relative difference between the reference and the measured velocity indicates the amount of decay between the two sensors. The relative decrease of stress wave velocity is determined in percent:

$$\Delta V_{rel} = \frac{V_{ref} - V_{mes}}{V_{ref}} * 100 \qquad \textbf{(1)}$$

where ΔV_{rel} is the relative decrease of sound velocity, V_{ref} the reference velocity and V_{mes} the measured velocity. The relationship between the relative velocity decrease and the area of decay is listed in Table 2 [9]. In terms of strength evaluation, it has been demonstrated that a 30 percent decrease in stress wave velocity corresponds to a 50 percent loss in strength in some species which in turn indicates severely decayed timber [10].

Besides the assessment of timber deterioration, stress wave measurements can also be used to predict mechanical properties of timber, i.e., the dynamic modulus of elasticity (MOE). The determination of the dynamic MOE is based on empirical relationships related to stress wave velocities and the density of timber established through experimental research. The dynamic MOE can be calculated derived from one-dimensional wave theory:

$$MOE_d = V^2 \rho \qquad \textbf{(2)}$$

where MOE_{d} is the dynamic MOE, V the wave propagation velocity and ρ the mass density. While one-dimensional wave theory is theoretically only valid for homogeneous and isotopic materials, several experimental research studies have shown that this theory is nonetheless appropriate for describing wave behavior in timber, and can therefore be utilized to estimate the dynamic MOE in a timber specimen based on measured stress wave velocities and density estimations. Since density measurements cannot be effectively taken non-destructively, tabulated values for various species are usually used. Alternatively, small samples can be taken from the timber specimen for laboratory testing of the density. However, small samples will only give local information, so multiple samples along the length of the specimen will be required to determine the global, overall density of the timber member [7].

In the stress wave method based on time-of-flight measurements, low frequency sonic stress waves, which are in the audible range, are generated and analyzed. Other techniques also use ultrasonic waves, which are of high frequency (above 20,000 Hz) and above the audible range. Using low frequency sonic waves with long wavelengths has the advantage that waves can travel larger distances and thus can provide an average of the material property of a specimen over its entire cross-section/length [11]. Ultrasonic waves, on the other hand, have short wavelengths and can only travel shorter distances due to higher attenuation. In stress-wave-based damage diagnosis, the detection resolution strongly depends on the wavelength of the generated sonic/ultrasonic waves. As an approximation, it is not possible to detect damage with a size less than half of the wavelength. Therefore, ultrasonic waves have a greater ability to detect subtle interior voids and defects than sonic stress waves [7]. Hence, choosing the right type of impact excitation is important and should be determined according to the dimensions of the investigated specimen and the defect size of interest. In general, sonic stress wave assessment is suitable for timbers with a depth greater than 89 mm, while ultrasonic testing is appropriate for smaller sizes.

1.2 Equipment

To measure stress wave propagation in structural timber, different commercial devices are available. Traditionally, commercial equipment was used for time-of-flight measurements in standing trees; the same equipment can, however, also be used on structural timber elements. Most commercial stress wave measurement kits are portable and battery-operated, and consists of two accelerometers, an impact hammer and an electronic unit. For testing, the two accelerometers have to be attached to opposite sides of the timber specimen through either a screw or a spike connection. By tapping one of the accelerometers with the impact hammer, a low frequency impulse is generated that travels through the timber. The recommended hammer weight is 100 to 200 g. The accelerometer on the opposite site of the impact measures the arrival of the generated stress wave. The time required for the wave to pass between the two sensors is computed and displayed/recorded in the electronic unit. Depending on the distance between the two accelerometers, the stress wave velocity is calculated and can be used to assess the condition and to determine the dynamic MOE of the timber specimen. With most devices, the spacing of the sensors must be measured manually, only some devices automatically calculate the sensor distance through laser measurements.

The following items are typically necessary for stress wave propagation testing: two accelerometers, an impact hammer, the electronic unit, cables, a rubber hammer, screws/spikes, a ruler, a moisture meter, and a thermometer. For in-field testing, it is advisable to bring spare batteries, cables and accelerometers.

2.3 Application

To measure the time-of-flight of stress waves in structural timber, the following steps should be carried out:

- Identification of testing site: Stress wave propagation testing should be conducted in areas that are highly susceptible to decay, such as in the vicinity of connections, bearing points or splashing zones. It is important that several sections at varying distances from the suspicious areas are tested [12].
- Attachment of sensors to timber specimen: The two measurement sensors must be tightly connected to the selected timber section using a screw or a spike connection (Figure 3). In the case of a spike connection, a rubber hammer should be used to drive the spike into the timber until a firm and stable connection is established. Depending on the accessibility and the desired path of stress wave travel, the sensors can be mounted in different positions, measuring either direct longitudinal, indirect longitudinal, transverse or semi-direct sound propagation (Figure 4). According to the mode of stress wave transmission, the spikes or screws should be connected either perpendicular to the surface (for direct longitudinal, transverse and semi-direct wave transmission) or at an angle α of approximately 45° (maximum 60°) between the sensor and the timber surface (for indirect longitudinal wave propagation).
- Measurement of distance between sensors: The shortest distance between the surface insertion points of the two accelerometers must be measured. For some devices, the distance between the impact location and the accelerometer insertion point must be determined.
- Power-on of the electronic unit: The electronic unit must be turned on to warm up the impact hammer and the accelerometers. One should wait at least a few minutes before starting the actual testing; waiting is especially important when using piezoelectric type sensors.
- Excitation of timber specimen with impact hammer: The start accelerometer must be hit using the impact hammer. To ensure precise excitation, the hammer strike must be performed in a straight manner along the line of the spike or screw. If the distance to the second accelerometer is comparatively large, a stronger hammer hit should be performed.
- Recording of the time-of-flight: The time-of-flight measurement displayed on the electronic unit must be recorded.

- Repetition of the test: The stress wave test must be repeated more than five times in order to obtain averaged stress wave propagation times to reduce uncertainties from individual testing. The first test should in general be disregarded. The larger the number of tests to be executed the more reliable and accurate the results.
- Determination of timber species: The wood species of the timber specimen must be identified using macroscopic and/or microscopic evaluation techniques. Knowledge of the correct wood species is necessary to determine reference stress wave velocities (Table 1). If the wood species cannot be identified or reference velocities are not sufficient, then stress wave tests on healthy sections of the same or another identical timber specimen must be performed. These measurements can then provide reference data for qualitative condition assessment.
- Measurement of density: If the dynamic MOE is to be calculated, the density of the specimen must be determined using a technique such as resistance drilling.
- Measurement of MC and temperature: The MC and the temperature should be measured using a moisture meter and a thermometer, respectively.
- Evaluation of test results: The stress wave velocities should be calculated using the measured sensor distance and the acquired time-of-flight recordings. Under consideration of the wood species, the annual ring orientation, the MC, the temperature and preservative treatment, the calculated stress wave velocities should be evaluated against reference wave velocities. Depending on the acquired results, a decision should be made if further measurements are required at or near the same location. In general, if the stress wave velocity is lower than 10% of the reference value or measurement results are fluctuating, the timber section should be suspected of having internal decay.
- Noting of testing conditions/abnormalities/special occurrences: The test set up should be noted or an appropriate sketch should be drawn containing information such as the location of the impact excitation and the accelerometers, the direction and arrangement of the sensors, and the orientation of the growth rings. The testing conditions (e.g., weather) and any abnormalities or special occurrences should be noted.

2.4 Result processing and interpretation

As highlighted earlier, stress wave measurements are affected by a number of conditions including the orientation of the annual growth rings, the MC, the wood species, temperature variations, and preservative treatments. Hence, to accurately evaluate and interpret the time-of-flight readings, it is crucial to understand and integrate these variables into the condition assessment process.

Effect of annual growth rings

The angle between the orientation of the annual growth rings and the impact direction greatly affects the time of stress wave travel in timber due to the unique cell structure of wood, and therefore has to be considered in the assessment of sound wave travel. As already stated above, the velocity of stress waves generated by transverse impact is about one-fifth to one-third of the wave velocity generated by longitudinal impact [8]. For transverse excitation, the relative angle between the impact direction and the grain orientation further influences the speed and pattern of stress wave travel due to the inhomogeneous nature of timber. The commonly accepted explanation for this phenomenon is that in transverse stress wave propagation, the wave can travel through the timber in three different ways, radially or tangentially to the growth rings, or across the rings at an angle between 0° and 90°, see Figure 5 (left). The slowest wave velocity for transverse excitation is for an impact of 45° orientation to the annual growth rings. The fastest velocity is experienced for radial excitation and is about 30 percent faster than with 45° orientated rings. For tangential excitation, the transmission time is about halfway between the radial and the 45° orientated impact. This relationship is illustrated for a typical healthy timber specimen of 12 percent MC in Figure 5 (right). In the depicted graph, the radial stress wave velocity is about 1500 m/s, the tangential speed is 1200 m/s and the velocity for 45° orientation to the grain is about 1000 m/s [12].

Effect of wood species

A key factor that influences the travel of stress waves in timber is the species of wood. In general, sound travels faster in hardwood species than in softwood species. For a large number of wood species, the stress wave velocities determined by various researchers are compiled in Table 1.

Effect of moisture content and temperature

The effect of MC and temperature on stress wave velocities in timber shows that for a MC greater than approximately 30 percent (i.e., above fiber saturation point), the wave velocity stays stable and shows little to no change. For a MC less than approximately 30 percent, the velocity of stress waves increases with decreasing MC. For fluctuating temperature, only small changes in wave velocities were observed. On average, an increase in temperature of 1°C results in a decrease of velocity of about 3 m/s in the temperature range of 0 to 40°C [9].

Adjustment factors for different MC and temperatures are listed exemplarily for Douglas-fir in Table 3.

Effect of preservative treatment

While the treatment of timber with waterborne salts has almost no effect on stress wave velocities, the treatment with oil-borne preservatives decreases wave velocities by about 40 percent compared to that of untreated wood [12].

2.5 Typical example

A typical example for the condition assessment of structural timber using stress wave measurements is described in the following case study. The health state of Douglas-fir timber beams, such as those depicted in Figure 6, is to be investigated. Visual inspection should always be the first step in every condition assessment task. If clear signs of rot, termite attack, or insect damage are spotted, the areas should be marked as potentially damaged and subsequently investigated. In the example, the end sections close to the walls are most likely to be prone to damage. Hence, stress wave readings should be taken at a minimum of two or three locations at the end regions of the beams (locations 1, 2, 4 and 5 in Figure 6). To obtain comparable data, it is also recommended to acquire stress wave readings from the middle sections of the beams (location 3 in Figure 6). Depending on the accessibility of the member, stress wave testing should be conducted in several directions, i.e., in transverse (sections A-B and C-D in Figure 7) and longitudinal (section E-F in Figure 7). In the example, the beams have direct access from both transverse directions; hence stress wave readings can be acquired across the width and the height of the beams. For longitudinal measurements, stress wave data must be acquired through indirect transmission with sensors installed at the side of the beams instead of the end faces.

The average time-of-flight recordings (average of five tests) acquired from locations 1 to 5 of the beam under investigation are listed Table 4. Further, MC and temperature readings are shown. For the longitudinal measurements (section E-F), only one recoding was taken at each of the two end regions. To determine the corresponding velocities, the time-of-flight recordings must be related to the respective distances between the two sensors. In this example, the distance for section A-B is 0.5 m, for section C-D is 0.2 m, and for section E-F is 1 m. The resulting stress wave velocities including the derivations are listed in Table 5.

To consider the influences of annual ring orientation, MC and temperature on stress wave propagation, the calculated velocities must be adjusted accordingly. As described above, for timber, the orientation of the annual growth rings relative to the impact direction is an important factor in the travel of sound waves. For an impact of 45° orientation to the annual rings, the velocity is 30 percent slower than for an impact in radial ring direction (90° orientation). Hence, for a ring orientation of approximately 75°, the wave velocity should be adjusted by 15 percent (adjustment factor of 1.15) to be comparable to radial reference velocities. Also, the influence of the MC, which ranges in the example from 10 percent to 23 percent, must be considered. While for MC of 10 to 12 percent, no adjustments are necessary; for 23 percent, the stress wave velocities have to be adjusted with a factor of 1.09 (see Table 3). With a temperature of 23°C, no adjustment is needed. The adjusted stress wave velocities and their derivations are listed in Table 5.

To evaluate the adjusted stress wave velocities in terms of timber deterioration, reference velocities must be determined. From Table 1, reference velocities for Douglas-fir can be approximated to 1200 m/s for impact in radial direction and 5000 m/s for longitudinal impact. With these values, the relative decrease of stress wave velocity can be determined according to Equation (1). The resulting values including their derivations are listed in Table 6.

From these results, it can be concluded that for the investigated beam, some deterioration exists at locations 1 and 2. The relative reduction in stress wave velocity is about 20 percent leading to the conclusion that approximately 10 percent to 20 percent of the area is deteriorated (according to Table 2). At the mid-span of the beam (location 3), no damage exists. Here, the stress wave velocities relate well with the reference values for sound timber. For locations 4 and 5, the relative velocities decreased by approximately 30 percent resulting in a decayed area of about 20 percent to 30 percent of the cross-sectional area.

2.6 Conclusions

Using stress wave measurements for the evaluation of the soundness of structural timbers is a simple and effective technique to detect and locate deterioration and to determine the stiffness (dynamic MOE) of a timber member. The successful application of the method requires proper execution of the stress wave testing and an appropriate evaluation of the measured stress wave travel times under consideration of influencing factors such as annual ring orientation and MC. The application of stress-wave-based health evaluation should always be used as one component of a comprehensive condition assessment procedure including visual inspection, knowledge of in-situ conditions and prior use of the timber member, and an understanding of fundamental engineering properties of wood.

3. Sonic/ultrasonic tomography

3.1 Basics

In this chapter, the use of time of flight (TOF) acoustic tomography to assess structural timber is discussed. Tomography refers to the cross-sectional imaging of an object from measurements collected on its external surface of energy that passes through the object itself. Different types of energy supply information on different physical properties of the investigated object. Acoustic tomography is a technique used to evaluate the material properties of objects using stress-wave propagation data. In acoustic tomography, typically the TOF) is measured. From the TOF and the distance between the sensors, apparent velocities are computed to obtain images of the velocity distribution throughout the inspected section. Acoustic tomography is applied to timber structural elements to detect (i) strength affecting heterogeneities (i.e., knots, checks, etc.) and (ii) damage (i.e., decay, cracks, etc.).

3.2 Equipment

In practical applications, most commonly, chains of electronically connected sensors are used [13,14] for cross- sectional or three-dimensional time of flight tomography. Figure 8 shows tomography equipment attached to the base of a timber post sitting on sandstone, as typically found in many historic churches. The boxes are connected with cables and include piezosensors or microphone sensors as well as electronic regulation for data filtering, processing and communication. Portable computers are used for data collection, storage, and display. Technically, the number of sensors is nearly unlimited, allowing the user to adapt the resolution to the given task. Three commercial manufacturers provide such systems and experts worldwide use them primarily to assess trees, but they are increasingly being used for timber structures as well. The equipment for scientific stress-wave TOF data acquisition [15,16] consists of:

- An oscilloscope, for visualization and analysis of the signal;
- A function generator, with a given pulse repetition frequency;
- A timer, which controls both the trigger of the generator and the counter;
- A signal amplifier;
- A signal filter;
- An instrumented hammer for emitting low frequency signals (< 10 kHz); or alternatively, a hammer to generate sound waves;

- Piezoelectric transducers, which are used for emitting high frequency signals (typically, 50÷100 kHz);
- Piezoelectric transducers for receiving the signal (or micro-accelerometers, in case of low frequency signal);
- Preamplifiers, which are required in most applications on wood, because of the high attenuation of the transmitted waves in the material, especially in case of thick elements.

For tomographic data acquisition, it is desirable to use a multi-channel device to speed up the measurements. Alternatively, a set of probes, operating both as signal emitter and receiver, can be used. In order to perform further analysis, the acquisition system is connected to a PC for data storage and signal processing. Coupling of the transducers to the wood specimen can be accomplished using a variety of materials (solids, liquids or air), depending on the circumstances of use. Gel type couplants are viscous and have good acoustic impedance; they can be used for rough surfaces and severely decayed members. To ensure consistent coupling pressure, avoid transducer misalignments. In order to facilitate simultaneous measurements from different points on the specimen, transducers can be fixed on special purpose guides or measuring frames that are fastened at the inspected section. Alternatively, pin probes can be inserted into the wood.

3.3 Application

In conventional tomography systems, an ordinary hammer is used to tap on the sensor or nail in order to induce a stress-wave. This strike initiates an electronic signal throughout the chain, starting all clocks to count microseconds until the stress-wave arrives at the corresponding sensor. This way, the time of flight is measured as well as any information on frequency and damping (Figure 9, a colored 2D-tomogram of a timber post, provides an excellent example of this). Colored lines between sensor positions indicate apparent stress-wave speed and are used to reconstruct the inner condition of the cross-section. Red lines do not represent the path of the stress waves but show areas where the measured waves traveled around an anomaly. Green indicates intact and mechanically connected parts. If required, resistance drilling or electrical impedance measurements are used to distinguish between different anomalies (i.e., decay or cracks).

Typical examples of TOF measurements are longitudinal measurements to detect cracks and delaminations in glulam beams and to estimate MOE, while density values are determined with resistance drilling (Figure 10). TOF measurements have been used in the assessment of historic structures that show signs of over-loading (Figure 11), and to assess beams in historic buildings without opening the floor (Figure 12). In this instance, stress wave sensors were placed along the supposed position of the beam. Time of flight values can indicate if a single beam spans the structure or if several beams have been used and if they are mechanically connected.

Acoustic TOF tomographic reconstruction generates the velocity distribution over a Cartesian grid of square pixels, according to the geometric arrangement of the sensors on the element surface. The definition of the parameters for data acquisition depends on the experimental conditions and the scale of the investigated characteristics. The minimum size of the detectable defects is pre-determined, depending on the frequencies used and resolution of the tomography. The resolution can be estimated from the calculation of the radius of the first Fresnel zone through the Equation (3):

$$R = \sqrt{\frac{d\lambda}{4}} = \sqrt{\frac{dv}{4f}} \qquad \textbf{(3)}$$

where *d* is the distance between the transmitting and the receiving point, λ is the signal wavelength, *v* is the velocity and *f* is the signal dominant frequency. Accordingly, shorter wavelengths allow the detection of smaller features. But short wavelength signals are more attenuated than long waves, therefore, a compromise between resolution and attenuation has to be found by choosing the frequency of the source. For this purpose, preliminary analysis of the acquired signal and evaluation of the signal-to-noise ratio should be performed. In general, ultrasonic tomography is better suited for compact and homogeneous elements, whereas sonic tomography is more appropriate for severely decayed elements.

The acquisition scheme for each specific test should be carefully designed, considering the characteristics of the investigated section (i.e., transversal or longitudinal) and the accessibility of the sensed surface. In particular, in the case of a transverse section, the presence and position of the pith and the orientation of annual rings should be considered to avoid the influence of anisotropy in the acoustic transmission along radial and tangential directions. If the pith is approximately centered in the section (which is the case of circular sections), or if annual rings are diagonally oriented (in rectangular sections), TOF data can be acquired from both opposite and adjacent sides (or all around the circumference) (Figure 13). In the other cases, and when annual ring orientation is unknown, acquisition should be performed only from two opposite sides (Figure 14) [14]. For longitudinal sections, to avoid the measurement of outliers caused by transmission along the fiber instead of across the fiber, the maximal inclination of the theoretically linear wave path should be considered. This can be done by a preliminary analysis of the average velocity values of a set of measurements along various paths [16]. In the case of a good signal-to-noise ratio (roughly greater than 6 dB), velocity can be measured visually on the oscilloscope using identification in a fully zoomed setting. This reading can be then confirmed using the saved computer data. Best results are obtained by scaling the waveform to saturation in the oscilloscope, in order to have a more accurate view of the first-arrival window. If signals are ambiguous due to strong attenuation, they should be appropriately filtered [17].

3.4 Result processing

The transit times, recorded for each pair of transmitting-receiving points, as well as the coordinates of these points, are the input data for the tomographic analysis. Methods adopted to reconstruct tomographic images from the time of flight data can be based on the assumption that the acoustic waves propagate in a straight line or, instead, along curved paths (bent rays). Different inversion algorithms can be adopted for tomographic reconstruction, among these, iterative inversion algorithms and direct inversion algorithms can be used [18,19].

Software for acoustic tomography are available for general applications on structures, but also specifically for applications to asses timber in structures and trees. Commercial software, however, is often linked to the use of tailor-made hardware for data acquisition. Operational limits are inevitably encapsulated in the software used for the tomographic reconstruction. Geometrical limits are typical, such as the shape or the maximum size of the inspected section, the maximal number of measurements or the minimum spatial resolution. A special attribute of the data inversion algorithm is the possibility to set global constraints, such as the upper velocity limit, to force the solution to reduce the non-uniqueness and to improve the consistency of the results. In this case, apparent velocities should be calculated, before inversion, for each source-receiver (S-R) position, as the ratio between the distance S-R and the measured travel time.

The assumption of anisotropy is another attribute of the inversion algorithm. Indeed, the difference between radial and tangential velocity can create artifacts in the tomographic image. Moreover, to adequately represent great velocity contrasts, such as those between decay/cavities and sound areas, a bent ray inversion approach is more appropriate than linear back-projection [20]. A velocity map can be represented by greyscale or color diagrams.

3.5 Interpretation of results

The representation modality of velocity maps, such as the chosen scale of the velocity values, can greatly influence the interpretation of results [21]. Image analysis techniques can be used to post-process the tomograms for a better interpretation of results. In order to highlight specific heterogeneities on tomograms, greyscale images can be segmented by histogram thresh-holding. Figure 15 shows and example where different features were detected according to the selected threshold. Methods of contrast adjustment using the image's histogram can be applied, such as histogram equalization techniques, to increase the global contrast of images when the usable data are represented by close contrast values (Figure 16).

Very high velocity values in acoustic tomograms of wood are generally associated with knots (Figure 17). Knots, however, can differ in their size, position, and condition, thus differently affecting wave transmission into the wood. Position and direction of tight knots, in transverse section can be estimated with a good approximation, while identification of loose knots is less accurate (e.g., in Figure 17 for the partially loose knot on the right upper corner of the section). Low velocity areas are associated with low material density, often caused by decay. Decay due to insect and fungal attacks can be detected by means of the acoustic tomography. However, the described technique permits only qualitative, large scale analysis (e.g., maps of entire elements), whereas complementary non-destructive methods should be used to obtain local quantitative information.

In general, it is recommended to couple acoustic tomography with local mechanical tests, such as resistance drilling tests, for the detection of internal zones of lower densities, and with visual/photographic analysis of the element faces for correlation of internal features and external indicators [22]. In order to distinguish pathological features of the material from other factors affecting acoustic wave transmission, velocity and other wave parameters could be analyzed. Moreover, diverse tomographic techniques, using different type of waves (e.g., electromagnetic waves), could be coupled. Analogously, acoustic tomography using different frequencies of the emitted signal could give information on different characteristics of the inspected section.

3.7 Conclusions

The main methodological aspects which influence acoustic tomography are the applied frequency, the number of independent measurements, the adopted acquisition scheme and the applied inversion technique. Because of natural variability and the anisotropy and inhomogeneity of wood, acoustic TOF tomography for the analysis of timber elements should be applied, taking into consideration all the operational requirements for data acquisition and interpretation. Since acoustic tomography is essentially non-invasive, it is possible to investigate large portions of a structure, although with less resolution than other techniques (such as local mechanical tests). Therefore, TOF tomography can be adopted as a large-scale global evaluation method for decay and defect detection, to be followed by further investigation in specific areas with anomalous velocity values.

4. Ultrasonic echo

4.1 Basics

The ultrasonic echo technique method can be used to assess the internal condition of timber elements [23-26]. The technique is based on the reflection of ultrasonic stress waves (longitudinal and transverse waves) from surfaces where the material change, such as the back surface of the specimen (which allows for determining the thickness of elements) or other interfaces, e.g., internal damage of the material. The low density of wood requires probes with high intensity and low-frequency (50-200 kHz); low frequency shear waves are best suited to assess wood. A low frequency results in a small attenuation of the signal; however, the large wavelength limits the size of the detectable defect accordingly. The first successful experiments were carried out with longitudinal waves by Hasenstab [23] using longitudinal wave transducers coupled by petroleum jelly, ultrasonic gel and glycerin. Because of the radial/tangential anisotropy on longitudinal waves, transverse wave transducers are now commonly used. Such transducers do not require a coupling agent since they are coupling by point contact, making the handling less complicated.

4.2 Equipment and application

The set-up consists of a signal generator, a preamplifier, an amplifier, a transducer and a PC for the data equalization (Figure 18). A sensor head developed by ACSYS [27] (shown in Figure 19) has 24 sensors; 12 sensors act as transmitters and 12 sensors act as receivers.

The ultrasonic echo technique needs access to only one side of the investigated element. During the measurement, the sensor is placed on a surface of the element. The sonic wave, illustrated by the arrows, passes through the element and is reflected from the opposite end of the specimen commonly referred to as back wall. The reflected signal is called back-wall echo and is received by the sensors. Any structural irregularity in the wood structure produces a change in signal structure of the back-wall echo. The simultaneous activation of all transmitting sensors reduces coupling problems on rough wooden surfaces and reduces the spread of the sound field when compared to a single sensor [24]. The probes are activated with a frequency of 55 kHz, which for pine assessed perpendicular to the fiber results in a wavelength of approximately 25 mm. Longitudinal wave transducers can also be applied, but these have to be used with a coupling agent like Vaseline. The resolution of the method strongly depends on the wavelength in the material. As an approximation, it is not possible to detect damages with a size less than a half the wavelength. Since the wave length in wood is 25 mm, it follows that it is not possible to use direct echoes to detect damage or anomalies with dimensions smaller than 12 mm. An increase of frequency is limited because higher frequencies result in higher attenuation of the ultrasonic signal with increasing current time [24].

4.3 Result processing

Results using the ultrasonic echo technique can be presented as A- and B-scans. The A-scan (Figure 20 right) shows the transmission time and intensity of the pulse; while the B-scan (Figure 20 left) is a composition of various A-scans that are recorded with a defined distance. The B-scan is a 2-dimensional cross section through the specimen and enables the identification of a change in signal structure along the measured axis. If several B-scans that are recorded with a defined offset are combined, it is possible to interpolate a horizontal layer. These interpolated layers (C-scan) can give 3D information about the structure and potential deterioration within the object [25]. When calibrated values are available (through measuring the dimension of the specimen other assessment methods), it is possible to determine the dimensions and inner structure of structural elements. Detailed tests and the application of NDT are recommended in areas with no or an unexpectedly early echo, because this can be a sign of damage. Figure 21 shows an example.

4.4 Conclusions

The ultrasonic echo technique allows for the direct localization of a reflector such as a back wall or any inhomogeneity or damage in the wood element. It is difficult, however, to locate the exact position of damage within the specimen. It is also difficult to distinguish between one large irregularity such as a knot or a cluster of small ones. Nevertheless, it can be assumed that a clear back wall echo shows that the specimen is free of defects [24]. Systematic measurements on specimens with artificial imperfections are required to make qualitative conclusions from measuring results. An exact classification of damage by analyzing the signal structure is not yet possible. The ultrasonic echo technique requires considerable experience because many of the parameters influencing the results are currently only partially known; nevertheless, the technique shows promise for in-situ timber assessments, as the detection of fungal decay has been successfully demonstrate [26].

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Tables

Table 1: Stress wave velocities of sound wood for different species, from [9,12,13] *Measured on tree

Species	Stress wave velocity (m/s)	
	Longitudinal	Transverse
White Ash	3968–5076	
Ash *		1,162-1,379
Beech *		1,670
Red Beech *		1,206-1,412
Birch	4695–5747	1,140–1,479
Yellow Birch	4348–5556	
Black Cherry	4831–5435	1,451–1,613
Horse Chestnut *		873-1,557
Sweet Chestnut *		1,215-1,375
Fir *		910-1,166
Black Fir *		1,480
Douglas-fir *		905-1,675
Japanese Fir *		1,450
Silver Fir *		1,360
Larch *		1,023-1,490
Lime *		940-1,183
Linden *		1,690
Black Locust *		934-1,463
Maple *		1,006-1,690
Sugar Maple	3906–5155	
Oak *		1,382-1,610
Live Oak		627–1,631
White Oak		1,258
Red Oak	3311–5650	1,548–1,751
Pine *		1,066-1,146
Scotch Pine *		1,470
Southern Pine	5000–5882	
Plane *		950-1,033
Black Poplar *		869-1,057
Pine Poplar *		967-1,144
Silver Poplar *		821-1,108
Yellow Poplar	5155–5747	1,399–1,479
Spruce *		931-1,310
Sitka Spruce	5882	
Willow *		912-1,333

Table 2: Relationship between relative velocity decrease and decayed area [9]

Relative velocity decrease in %	Decayed area ratio in %
0 - 10	No decay
10 - 20	10
20 - 30	20
30 - 40	30
40 - 50	40
≥ 50	≥ 50

Table 3: Stress wave velocity adjustment factors for different MC and temperatures for Douglas-fir, adapted from [12].

MC (%)	Adjustment factors			
	-18°C	3°C	27°C	49°C
1.8	0.94	0.95	0.97	0.98
3.9	0.95	0.96	0.98	0.99
7.2	0.93	0.98	1.00	1.01
12.8	0.97	0.99	1.00	1.01
16.5	0.99	1.01	1.03	1.05
23.7	1.05	1.07	1.09	1.14
27.2	1.07	1.1	1.12	1.17

Table 4: Time-of-flight recordings, MC and temperature measurements

Location	Stress wave transmission time (µs)			MC (%)	Temperature (°C)
	A-B (≈ 75° to grain)	C-D (radial)	E-F (longitudinal)		
1	614	207	253	12.4	23
2	620	206		12.3	23
3	503	160	196	10.2	23
4	751	256	297	22.8	23
5	758	247		22.6	23

Table 5: Calculated and adjusted (in parenthesis) stress wave velocities

Location	Stress wave velocity (m/s) A-B (≈ 75° to grain)	 C-D (radial)	 E-F (longitudinal)	MC (%)
1	814 (936)	966	3953	12.4
2	806 (927)	971		12.3
3	994 (1143)	1250	5102	10.2
4	666 (835)	781 (852)	3367 (3670)	22.8
5	660 (827)	810 (883)		22.6

Table 6: Relative decrease in stress wave velocity

Location	Relative decrease in stress wave velocity (%) A-B (≈ 75° to grain)	 C-D (radial)	 E-F (longitudinal)
1	22.0	19.5	20.9
2	22.7	19.1	
3	4.7	-4.2	-2.0
4	30.5	29.0	26.6
5	31.1	26.5	

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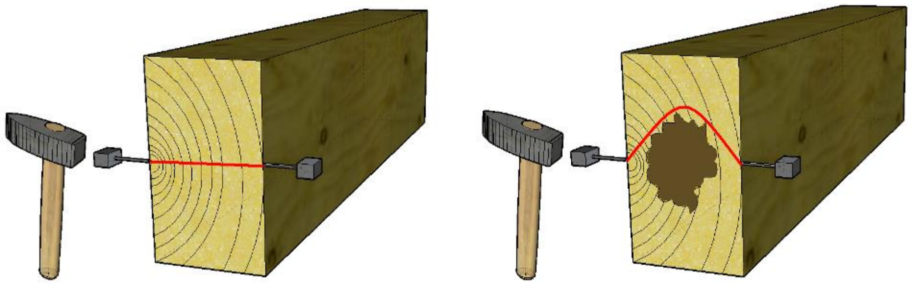

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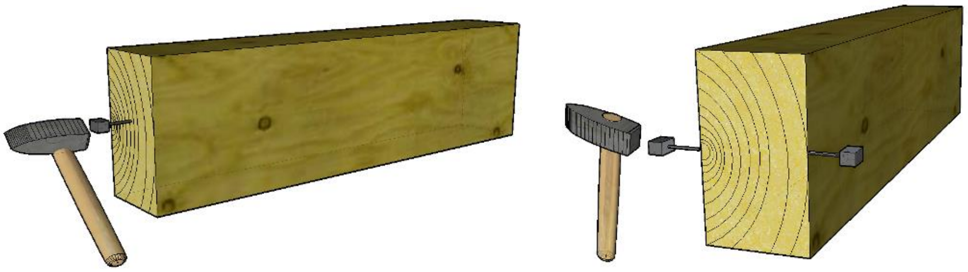

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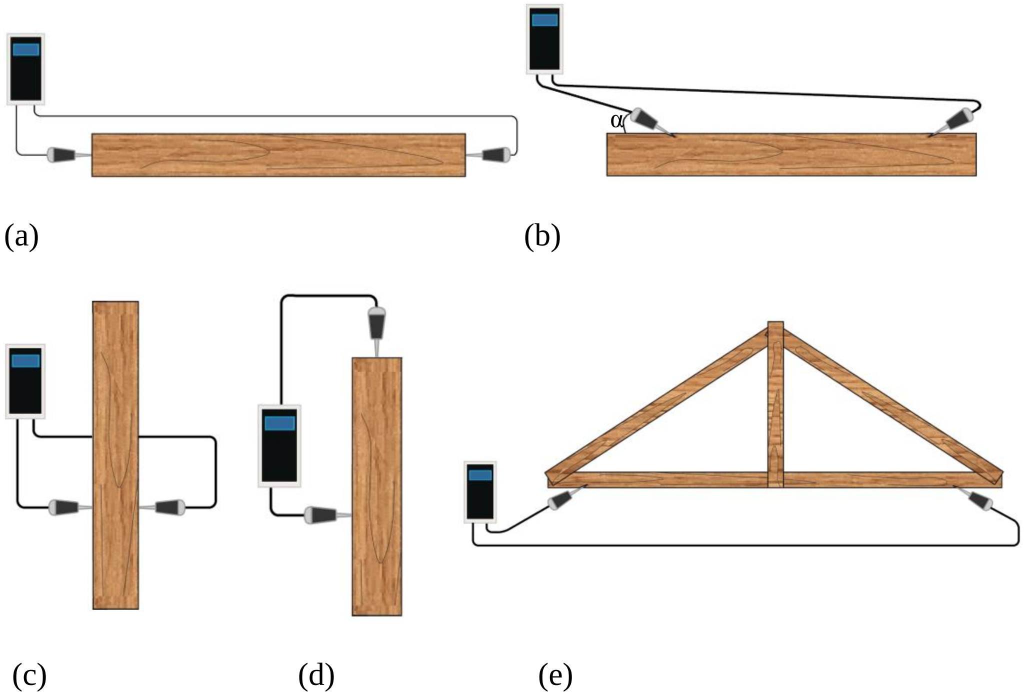

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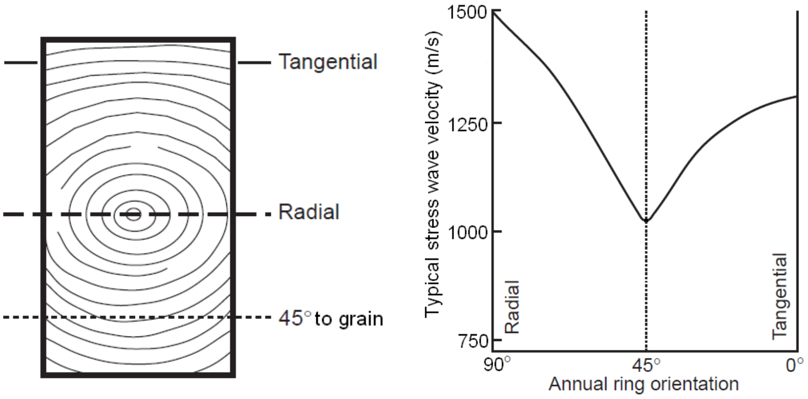

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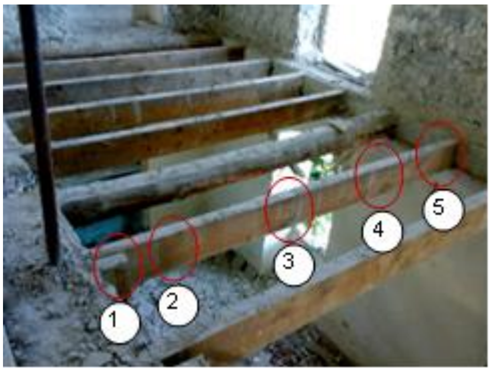

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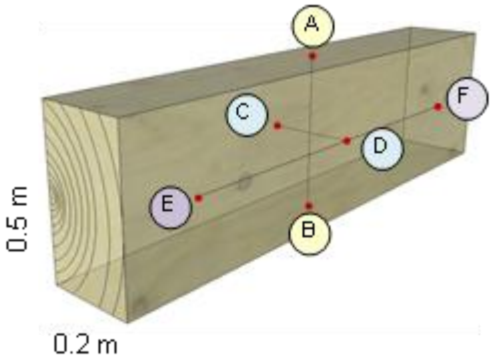

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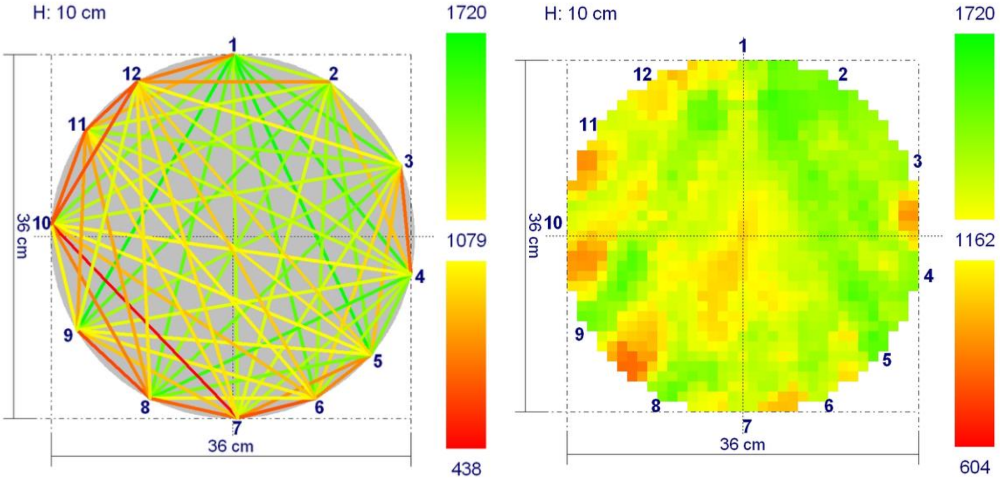

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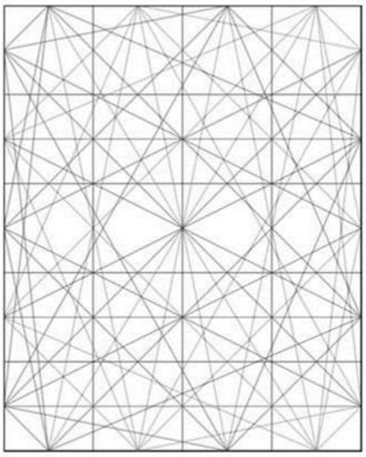

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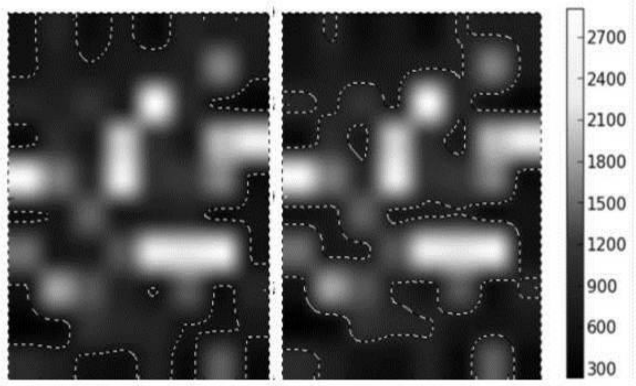

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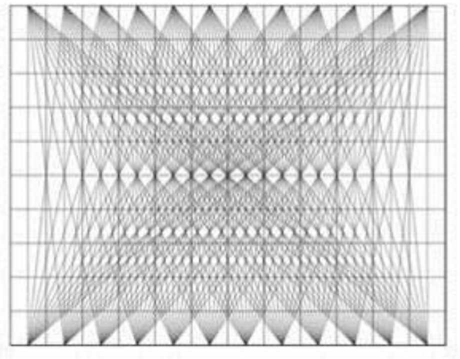

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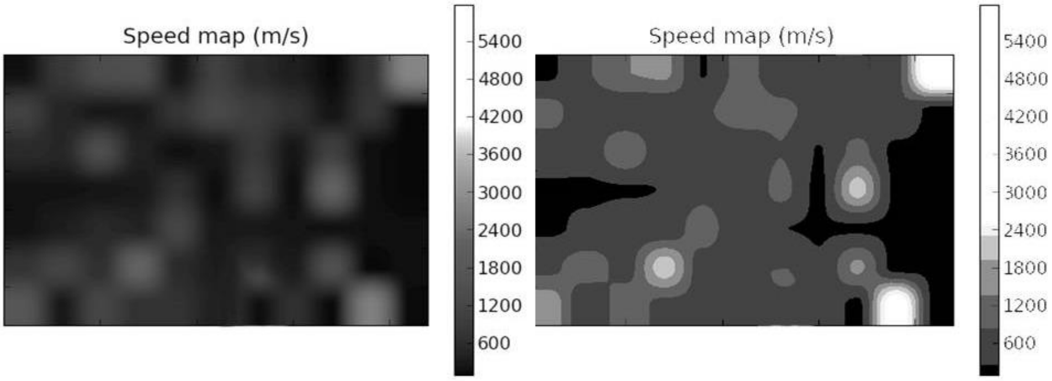

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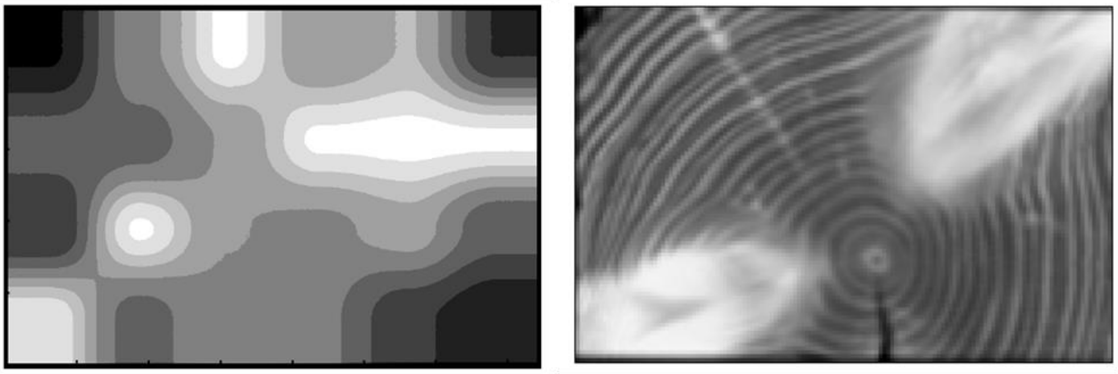

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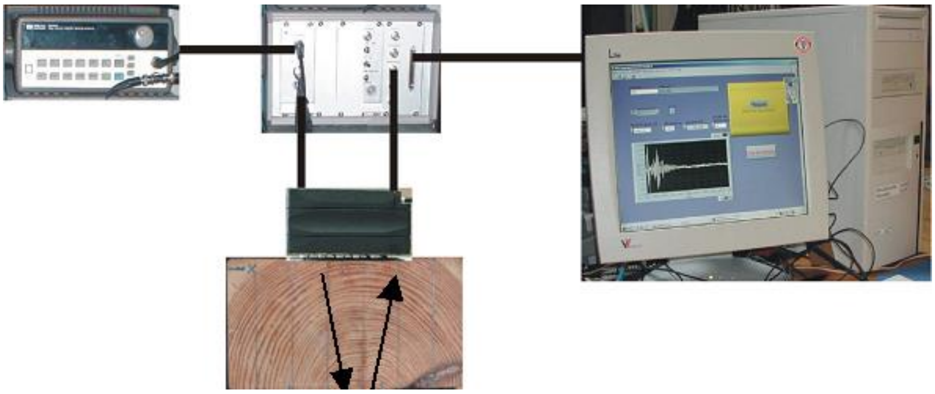

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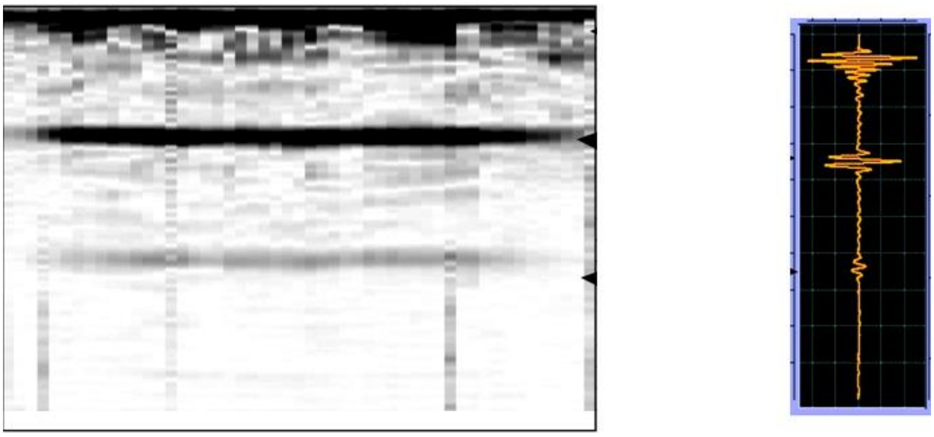

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