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Non-destructive testing of wood and wood-based materials

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ABSTRACT

Methods of non-destructive wood testing continue to gain importance. Online tools, for example to control production, have effectually been in use for years. Based on a measuring systematics (physically active principle and important influencing factors), a summary of methods to assess cultural heritage objects is given. To adopt methods based on physical effects, profound knowledge of wood physics is essential, particularly knowledge of interdependencies.

1. Research aims

This paper gives an overview on various methods available for the non-destructive inspection of wooden cultural heritage objects.

2. Introduction

Wooden cultural heritage objects are exposed to numerous stress factors:

- usage (mechanical wear, impact of fluids [e.g. water damage]);
- mechanical long-term load and subsequent effects thereof, such as creeping or relaxation (e.g. musical instruments under pretension such as violins, pianos, etc.);
- stresses induced by moisture changes, in particular in glued components (e.g. veneered furniture, plywood elements); effect typically occurring under low relative humidity conditions (< 20% RH) for example during winter-time in heated rooms;
- insect attack;
- fungal decay occurring for wood moisture contents more than 20% (typical problem in building and civil engineering, relatively uncommon for other kinds of wooden cultural heritage objects).

Generally, it can be assumed that wood properties scarcely change under dry conditions; only a certain reduction in the variation of the equilibrium moisture content occurs due to the reduction of residual stresses [1]. Crack formation and delamination are more likely occurrences, in particular in cultural heritage objects with a veneered surface (in the past, the supporting material for the veneer surface was typically solid wood, which shows more swelling than materials used nowadays as supporting material, such as plywood or MDF). Furthermore, properties of materials used in the past as adhesives (e.g. bone or fish glue) and for the surface treatment (e.g. shellac, lacquer, etc.) differ conspicuously from the properties of modern materials. The materials used in the past were generally more elastic but less moisture resistant. Reliable characteristics for these properties are practically unavailable as the materials are scarcely used nowadays.

For the assessment of cultural heritage objects a variety of techniques is required. The basis for any reliable evaluation is thorough knowledge of the properties of wood as a basic material. In addition to simple tests, such as visual inspection with a magnifying lens or manual scanning/knocking for surface defects, non-destructive testing methods can also be used to contribute towards findings. In the following we give an overview of such methods. The focus lies on methods suitable for the study of cultural heritage objects. Methods for structural analyses, as well as methods used predominantly for scientific research (e.g. X-ray imaging at synchrotron sources) and also methods used for strength grading are not included. Likewise, chemical analyses for the determination of emission or wood preservatives are excluded.

3. Wood and structural element properties in the field

3.1. Wood properties

Assessing the age of wood is very difficult due to the high variability of wood properties (e.g. density, mechanical strength, colour, etc.) and the unknown initial state. For comparison, only

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highly varying reference values can be found in literature. Certain wood properties alter over the course of time bringing about gradual changes. Often moisture fluctuations superimpose each other. The great variability of wood properties is shown in the following example of characteristic values of Norway spruce (*Picea abies*) [2]:

- quality indicators (density, modulus of elasticity (MOE), modulus of rupture [MOR]):
  - density: 300. . .640 kg/m^3,
  - MOR: 49. . .78. . .136 N/mm^2,
  - MOE: 7300. . .11000. . .21400 N/mm^2;
- colour value, also in colour changes due to natural aging;
- the equilibrium moisture content (EMC) does not vary significantly, nevertheless the variation coefficient decreases considerably with age.

Yokoyama et al. [3] state that aged wood does not show significant variations of rigidity (in longitudinal and radial direction) or strength (longitudinal); but they further state that the wood age drastically influences the post-linear behaviour, where the strength and rupture energy, especially perpendicular to the grain decrease markedly.

During storage and natural aging several changes can occur: colour changes (brightening/darkening); spruce wood darkens through aging while maple wood and birch subdues to strong yellowing, other wood species brighten to different degrees. Other changes that can occur include surface roughness and erosion of early-wood under exposure to UV-radiation and water (Fig. 1) [4].

3.2. Properties of structural elements

Failure of wooden structural elements caused by pure mechanical load rarely occurs in cultural heritage objects. Failure can occur in adhesive joints caused by permanent swelling and shrinkage in long-term experiments (e.g. delamination, crack formation, etc.) (Fig. 2). Swelling and shrinkage and the resulting stresses can cause crack formation in wooden frames or fillings. The effects of pretensioning, for decades or centuries in musical instruments for example, are scarcely known. Due to rheological behaviour, relaxation and creep can be expected, which can even be amplified by the mechanosorptive effect of superimposed moisture changes. An overview on the properties of wood for musical instruments is given by Bucur [5].

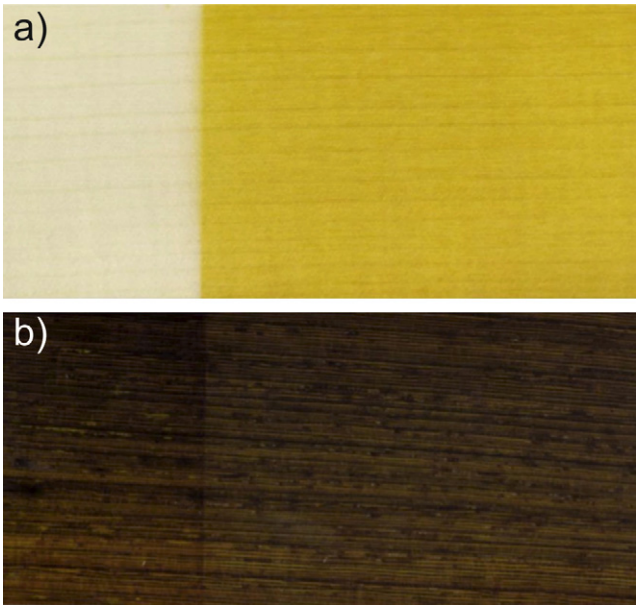

Fig. 1. Colour change of parquet (top: Sycamore maple (*Acer pseudoplatanus*) bottom: Panga panga (*Millettia stuhlmannii*)) under light exposure; the left third shows the initial colour, the left two-thirds the discolouration.
Source: [4]

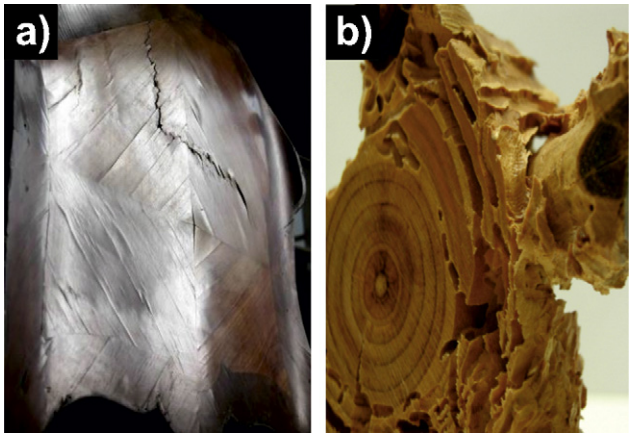

Fig. 2. Crack formation and delamination (a) as well as insect attack (b) in musical instruments caused by ongoing moisture changes.

4. Basic principles of non-destructive testing methods

4.1. Methodological approach

Nowadays, the most common approach is to use multisensor techniques, i.e. a combination of several measuring methods, because a single parameter is generally insufficient to concisely describe the condition of an object or material. Smaller defects such as small knots or cracks are, for example, scarcely detected using simple sound transmission measurements.

Methods used in the context of automated production use mostly a combination of several measuring instruments to assess if the target parameters, which are computed using mathematical methods, conform to the guideline values. Such methods are mostly too intricate and impractical to be used for the evaluation of cultural heritage objects, so the utilisation is limited to few individual cases. Fig. 3 shows the basic concept. Nowadays, the whole spectrum of physical properties of wood is used for the non-destructive testing of wood.

An overview on the selected physical wood properties and their usability for non-destructive testing for wood and wood-based materials is given in Table 1.

For the assessment of cultural heritage objects, only some of the available non-destructive testing methods can be considered. These are essentially:

- measurements of the moisture content;

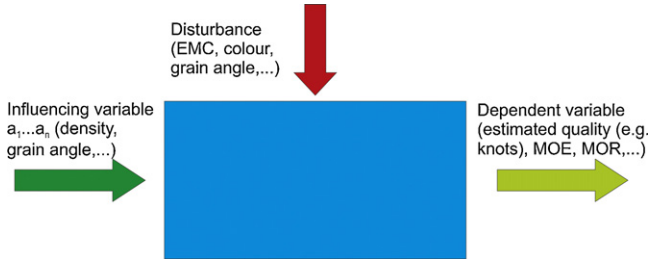

Fig. 3. Basic concept of non-destructive testing methods; combination of different methods: $y = f(a_1 \ldots a_n)$, where y is a mathematical model or estimation from testing person.

Table 1
Summary of methods for non-destructive wood testing.

Property	Basic physical principles	Measurable properties	Suitability for investigating cultural heritage
Mechanical properties	Drilling resistance, hardness, intrusion behaviour	Detection of fungal decay, density	x
Electrical properties	Electrical resistance		x
	Correlation between electrical resistance and moisture content	Moisture content	x
	Correlation between electrical resistance and fungal decay	Detection of fungal decay	x
	Dielectrical properties	Moisture content	
Acoustical properties	(Ultra-)sound-velocity, -reflection, -attenuation	Elastic constants (E, G) Defect detection (knots, cracks, delamination)	
	Acoustic emission	Micro cracks, insect noises	(x)
	Eigenfrequency	Elastic constants (E, G) Delamination in glued wood joints	x
Thermal properties	Heat radiation (thermography)	Defects on near-surface areas (failing adhesion of inlays, opened fugues)	x
Particles	Neutron radiation	Allocation of humidity Wood preservatives (penetration behaviour)	x (only at few large scale facilities)
Electromagnetic waves	Microwaves	Grain direction, density	(x)
	IR/NIR radiation	Humidity, chemical analysis (impurities), partly mechanical attributes	(x)
	Visible light	Colour measuring (CI-Lab) → aging, colour differences/changes	x
		Video image correlation → cross correlation, strain distribution	x
	X-ray (tube)		
	Absorption	Density, local density allocation, annual growth ring profiles	x
	Diffraction	Microfibril angle in S2-layer	(x) Complex equipment, mainly laboratory testing
	X-ray (synchrotron)	Microstructure analysis	x (only at few large scale facilities)

- strain measurements;
- colour measurements;
- delamination surveys;
- computed tomography (mainly based on X-ray transmission measurements): ascertainment of defects within the material (rot, insect attack, cracks), the material composition/object construction, age dating (growth ring analysis);
- ultrasound: assessment of mechanical parameters;
- video image correlation: determination of distortion during mechanical load or moisture induced stresses;
- thermography: detection of veneer delamination;
- chemical analyses using spectroscopy: verification of applied surface finishing/wood preservatives, correlation of physico-chemical properties, etc.

Alongside such methods, visual inspections and classical microscopic methods can still be very helpful. Table 2 gives an overview of the methods with their objective target.

A good overview on the right methodology to solve problem non-invasively is for example given in the works by Hellier [6] and Shull [7]. Bucur [8] reports on existing non-destructive characterisation and imaging methods for wood.

Table 2
Overview of available testing methods, sorted along the objective target.

Target objective	Method
Layer thickness measurement	Optical, electrical
Structural analyses	Increment borer, tree ring analyses, fractometer computed tomography (using e.g. X-ray, neutrons, ultrasound), microscopic (SEM, optical)
Age dating	Dendrochronology (based on: optical assessment, X-ray densitometry, neutron imaging, etc.), radiocarbon dating C14,
Moisture content, Moisture distribution	Electrical, dielectrical, NIR-spectroscopy (only surface humidity), neutron imaging, gravimetric (kiln drying)
Chemical composition	IR, NIR-spectroscopy, wet chemical analyses
Delamination of bonded joints, coatings	Ultrasound, X-ray imaging, thermography
Inner defects (insect attack, rot, cracks)	Computed tomography (based e.g. on X-ray, sound (low spatial resolution) or electrical resistance), drilling resistance,
Strength	Sound, mechanical loading, eigenfrequency
Colour	Colour measuring instruments (CIE Lab)
Structural changes under load	Sound emission
Distortion und mechanical or climate-induced load	Video image correlation/photogrammetry Electronic speckle pattern Interferometry
Gloss	Gloss level measurement
Strain gauging	Video image correlation/photogrammetry

5. Short overview of commonly applied methods

5.1. Mechanical tests

5.1.1. Deformation measurements

Deformation under given load is measured to assess the modulus of elasticity and the strength (using the correlation between modulus of elasticity and strength) (Fig. 4) [9]. The calculation,

Fig. 4. Deformation measurement on a wooden bridge.
Photo: FPL Madison, [9].

which follows the laws of technical mechanics, takes into account the component geometry, the load and the deformation.

5.1.2. Drilling resistance

Drilling resistance assessment uses the drilling power input with a small diameter needle as a function of the covered distance. If the drill needle encounters a cavity or decayed areas, then the power input decreases, hence the defect is visible in the drilling resistance profile (Fig. 5). Small defects are scarcely detectable [10].

5.1.3. Hardness

Hardness can be determined by measuring the penetration depth of a needle applied with a constant load. The penetration depth correlates with the density. Only external defects can be assessed.

5.2. Sound and eigenfrequency measurements

5.2.1. Speed of sound/sound attenuation

The propagation velocity of sound waves depends on the elastic properties of the material. Using the speed of sound and the density it is possible to determine the modulus of elasticity using longitudinal waves [equation (1)] and the modulus of shear using transversal waves (Fig. 6) [11].

The modulus of elasticity can be calculated for a beam (without taking into account Poisson's ratio) along equation. (1):

$$E = v^2 \cdot \rho \quad (1)$$

E – Modulus of elasticity N mm^{-2}
ρ – raw density in kg m^{-3}
v – speed of sound in m s^{-1}

If the object/material features cavities or cracks running transverse to the sound propagation direction, then the distance covered

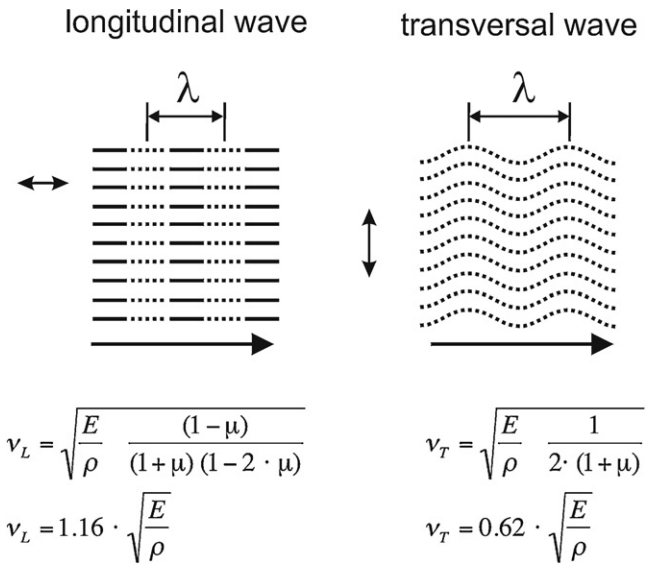

Fig. 6. Types of wave propagation (equations valid for isotropic bodies).
Source: [11].

by the sound waves will be longer, hence the determined speed of sound will be lower. Nevertheless, a defect has to be relatively large in comparison to the component/object to be detected. If several sensors are placed along the periphery of an object, then it is possible to assess the two-dimensional sound propagation using sound-tomography (Fig. 7). The reflection method can be used to determine density distribution on the surface.

Contact-free measuring methods have been in utilisation for several decades in the wood panel industry. Here, the attenuation of the sound waves at the air/solid transition-zone is used. This principle can also be used for the detection of delamination in glue-laminated timber [12].

Moduli of elasticity determined using speed of sound measurements are in general 10 to 20% higher than values determined in static experiments. For sound transmission measurements on wood, relatively low frequencies between 20 and 50 kHz with corresponding wavelengths in the centimetre range are required. Hence, smaller defects such as knots, small cracks and local inhomogeneities can scarcely be detected. The porosity of wood entails higher frequencies, as used for metals and other materials, and high sound attenuation. Thus, only small wood objects can be examined with these frequencies. Inner defects can be detected using the impulse-echo principle [13,14].

5.2.2. Eigenfrequency measurements

Elastic constants can be calculated using the eigenfrequency of an oscillating sample. The flexural modulus of elasticity can

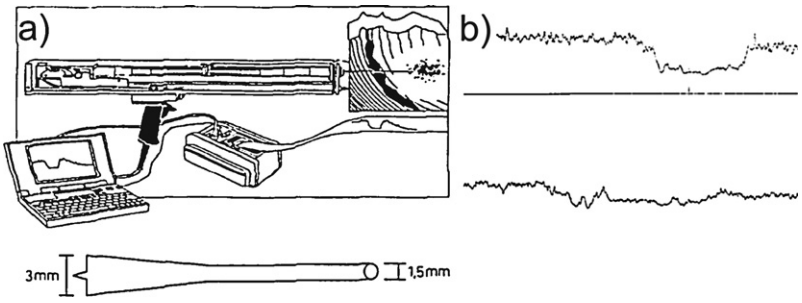

Fig. 5. Drilling resistance measurements (Rinntech®, /IML); a) measuring instrument b) drilling resistance profile (above: with decayed region; below: sound wood).
Source: [10] modified.

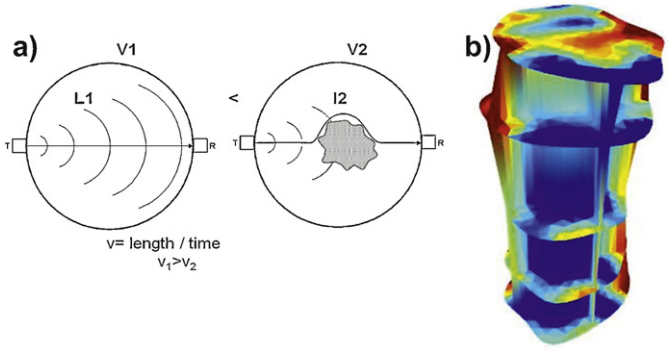

Fig. 7. a) Sound propagation in sound wood (left) and wood with a defect (right) (P. Niemz, ETH), b) Sound-tomography of a stem (Picus/Germany).

be calculated for rectangular bars using bending waves [equation (2)], longitudinal waves can be used to calculated the modulus of elasticity under compressive load [equation (3)]:

$$E_{dyn} = \frac{4 \cdot \pi^2 \cdot l^4 \cdot f^2 \cdot \rho}{m_n^4 \cdot i^2} \cdot \left(1 + \frac{i^2}{l^2} \cdot k_l\right) \cdot 10^{-9} \quad (2)$$

$$E_{dyn} = \frac{4 \cdot l^2 \cdot f^2 \cdot \rho}{n^2} \quad (3)$$

E: MOE [N/mm^2]
l: length [mm]
f: frequency [s^{-1}]
ρ: density [kg/m^3]
K_1, m_n: constants (depending on order of oscillation)
i: radius of gyration [mm]

Fig. 8 shows the experimental setup for eigenfrequency measurement [15]. The modulus of elasticity values derived from such measurements show a very high correlation with values determined with mechanical tests. The procedure is nowadays a regularly used method in wood industry for strength grading. Furthermore, a shear modulus can be determined using free-free bending vibrations.

5.2.3. Sound emission

Sound emission comprises signals that are emitted in material under load (far below the actual fracture load) by microfractures. The sensors used for such measurements are sensitive for frequencies in the range of 200 kHz. The method can be used for the detection of structural changes (microfractures), fractures occurring during the wood drying process and for confirmation of insect attack. The following parameters can be assessed: number of signals exceeding an adjustable threshold, sound energy of the individual signals, and analysis of the signals frequency distribution.

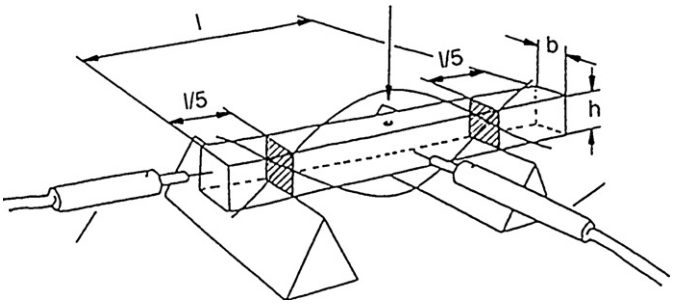

Fig. 8. Experimental setup for eigenfrequency measurements [15].

5.3. Electromagnetic radiation

5.3.1. X-ray/synchrotron

Electromagnetic radiation is attenuated by matter. The attenuation follows Beer-Lambert's law [equation (4)]:

$$I = I_0 \cdot e^{-\mu \cdot d} \quad (4)$$

where I is the intensity of the transmitted beam, I_0 the intensity of the incident beam, μ is the attenuation coefficient and d is the thickness of the object in the beam direction.

The attenuation coefficient μ is a material parameter describing to what extent matter attenuates the radiation. It depends on the elemental composition and the density, which allows deducing the density ρ from X-ray images following equation (5).

$$\rho = -\ln\left(\frac{I}{I_0}\right) \cdot \frac{A}{N_A \cdot \sigma \cdot d} \quad (5)$$

where σ is the microscopic cross-section of an element, A is the atomic weight and N_A is Avogadro's constant. Also the moisture content can affect the total attenuation coefficient of a wood sample, especially if high moisture contents beyond the fibre saturation point are present or if the X-ray source is operated with relatively low voltages.

Single transmission images can thus yield 2D information on the structure and density distribution within an object. Furthermore, a computed tomography (CT) allows obtaining 3D information on the studied object. By gradually turning the object and gathering images from different angles, it is possible to reconstruct a volume data set, containing information on the attenuation and thus the material for every point (voxel) within the volume (Fig. 9) [16]. Tomography data allow ascertaining the density distribution/profile within an object and can help to determine inner defects.

Besides transmission measurements it is also possible to use backscattering, which is for example used for the determination of density profiles perpendicular to the surface of wood-based materials.

Some examples for the utilisation of X-ray CT are shown in Fig. 10 [16–18]. In contrast to CT data based on ultrasound measurements, X-ray CT allows for much higher spatial resolution.

Typical implementations are:

- determination of density and density profiles (X-ray scattering);
- detection of knots;
- detection of decay.

The spatial resolution obtained can vary considerably depending on the equipment and experimental setup used:

- medical scanners more than 100 μm/px;
- standard X-ray scanners 10–100 μm/px;
- X-ray microfocus 2–5 μm/px;
- synchrotron microtomography <1 μm/px.

These setups also determine the size of the studied objects. Large objects (e.g. sculptures, trees, etc.) can only be examined using standard (or medical) X-ray scanners. Investigations with high spatial resolution (e.g. at a synchrotron facility) are limited to sample sizes of a few millimetres.

5.4. Colour measurement/gloss level/spectroscopy

5.4.1. Colour and gloss level

Wood undergoes colour changes caused by oxidation. Different systems are available to measure the extent of colour change, the most common system being the CIE Lab-system (Fig. 11). Here,

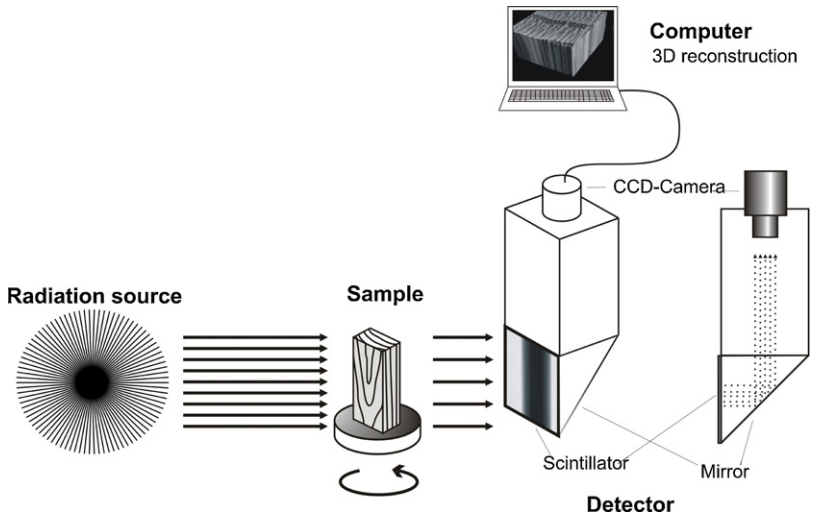

Fig. 9. Basic principle of computed tomography measurements [16].

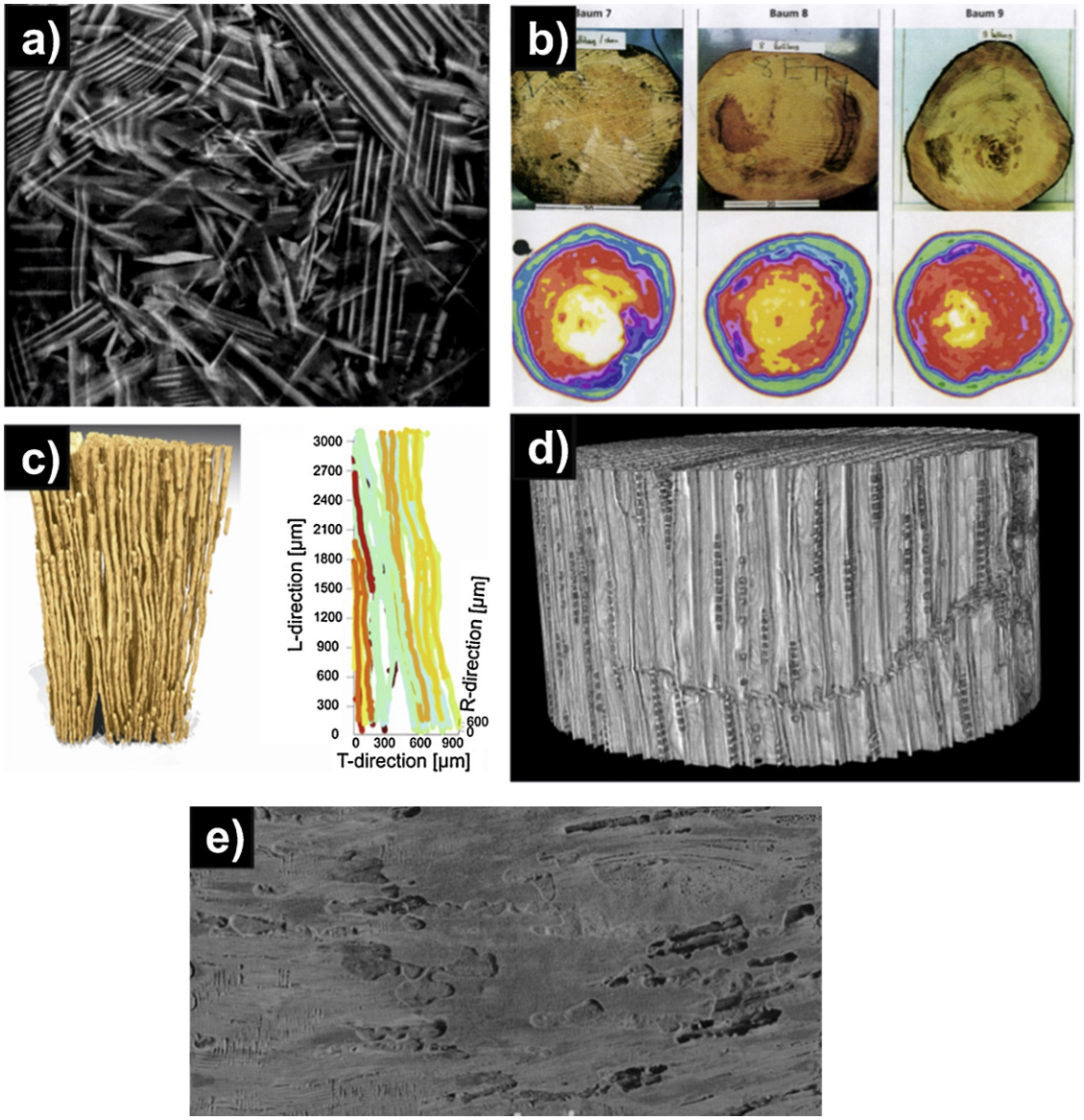

Fig. 10. Examples for X-ray tomography: a) tomogram of an OSB-panel, b) mobile X-ray CT on standing trees, c) synchrotron microtomography of the vessel network in beech wood (Fagus sylvatica) [17] d) fault line in spruce wood [18] and e) virtual cut through of an adhesive joint of 1 C PUR (synchrotron microtomography) [16].

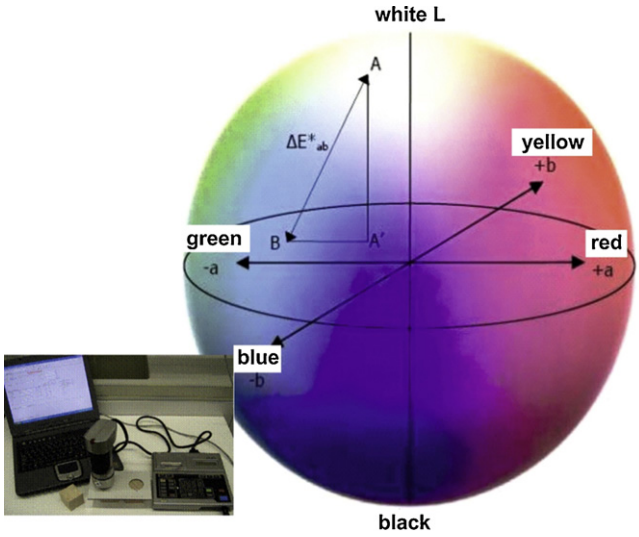

Fig. 11. CIE Lab colour measurement system defining the colour in a three-dimensional colour space (source: CIE, Vienna).

the colour can be described as a coordinate in a three-dimensional space; the three coordinates are: L* the lightness of the colour; a* position between red and green; b* position between yellow and blue.

The gloss level of coatings is determined by comparative measurements with a reference standard. The test results are not referenced against the quantity of the incident light but a polished, black glass reference standard with known refraction index.

5.4.2. Spectroscopy

The correlation between the chemical and physical-mechanical properties of wood is an increasingly important methodology. Near-infrared (NIR) spectroscopy allows chemical characterisation of the material and correlation of the determined composition against a corresponding command variable by means of multivariate statistics. This allows assessment of the mechanical strength as well as the chemical composition [19–21]. Some examples are shown in Fig. 12 [22].

5.5. Optical imaging methods (video image correlation)

Cross correlation, a method known from photogrammetry, allows for the quantification of the displaced pixels in a series of images. For this kind of measurement, several systems are available, which can for example be used to determine the displacement (in 2 or 3D) of a speckle pattern applied to the surface of a sample and then exposed to mechanical loading. An example is shown in Fig. 13 where the strain of a tensile specimen under varying load is monitored using a CCD-camera.

Other related systems are based on the evaluation of reflected laser signals (ESPI) on the specimen surface. This technique can be used to assess e.g. swelling, distortion and mechanical load.

5.6. Moisture measurement

For the determination of the moisture content, several measuring systems are available, using the principle of resistance measurements (correlation of wood moisture content with electric resistance), measurements of the dielectric coefficient, the

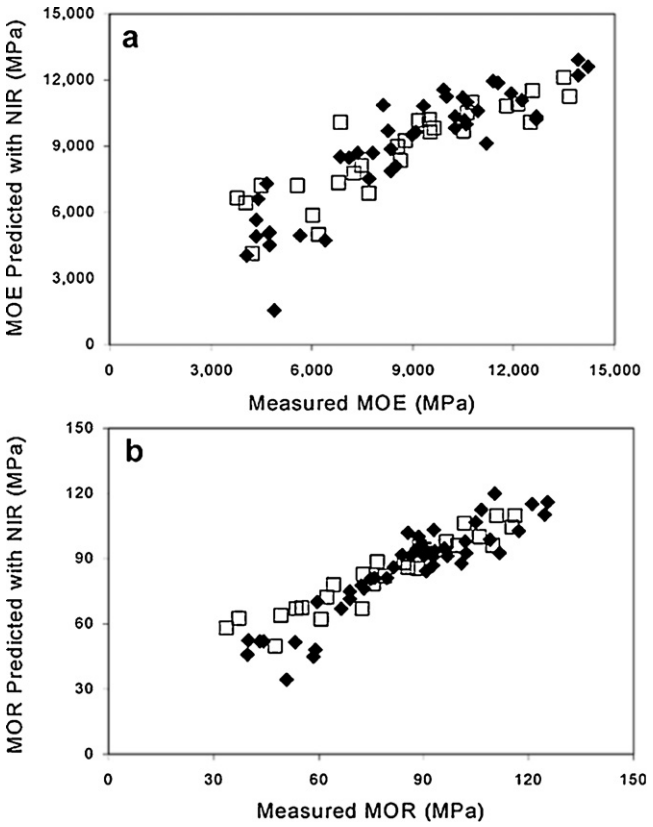

Fig. 12. The results of the PLS-2 models showing the correlation between measured mechanical properties and the mechanical properties of (a) MOE and (b) MOR predicted with NIR spectra collected over the full spectral range (500–2400 nm). Solid symbols are samples included in the CALB set and open symbols are samples included in the TEST set [22].

absorption of microwaves as well as optical systems (based on NIR-spectroscopy) (Fig. 14) [23].

Objects with a large cross-section never reach equilibrium moisture content over the whole cross-section. Therefore, the moisture content has to be determined as a function of the depth (e.g. electrodes at different depths), which allows for the assessment of moisture profiles. The moisture content on the surface can be determined using NIR techniques; here, the absorption of waves with a wavelength of 1930 nm is evaluated as a function of the moisture content. The penetration depth of this radiation is less than 0.1 mm; the method applies for loose material as well as for moisture measurements on the surface (crucial information for e.g. the utilisation of 1C-PUR). Electric resistance measurements (resistance tomography) can also be used for the detection of rot (Fa. Picus/Germany).

Besides these standard methods, neutron imaging represents an alternative method to determine the moisture content. Neutrons have a high interaction probability with hydrogen. This allows for a quantitative determination of the moisture distribution within a sample with high spatial resolution [16,24,25]. Fig. 15 shows the moisture distribution determined by means of neutron imaging within a multilayered sample [24].

5.7. Coat thickness measuring

Several methods are available to determine the thickness of coatings (Fig. 16) [26,27]:

- ultrasound;

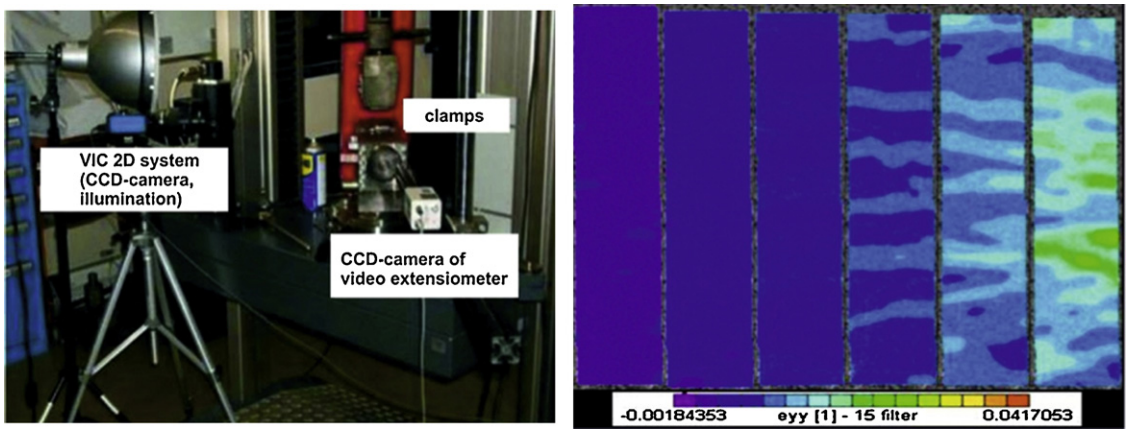

Fig. 13. Video image correlation (left) experimental setup; (right) test result showing the distortion of a tensile specimen under varying load.

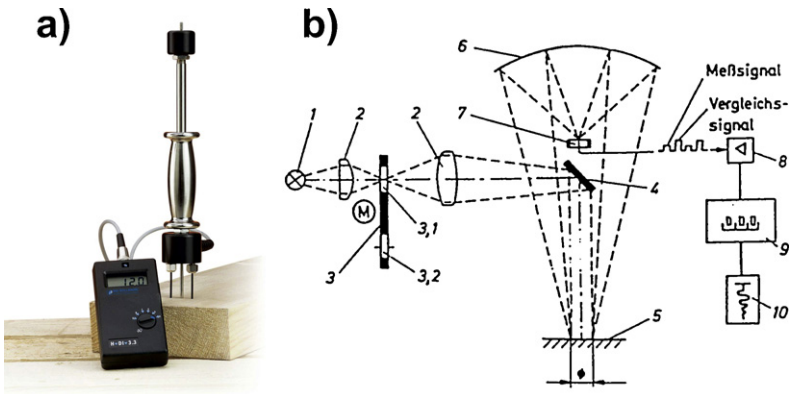

Fig. 14. Moisture measurements: a) electrical resistance measurement between two electrodes (BES Bollmann), b) working principle of NIR-spectroscopy measurements. *Source b: [23].*

- electrical resistance;
- optical systems.

Furthermore, measuring devices exist, which use the measurement of the gloss level compared to a reference standard.

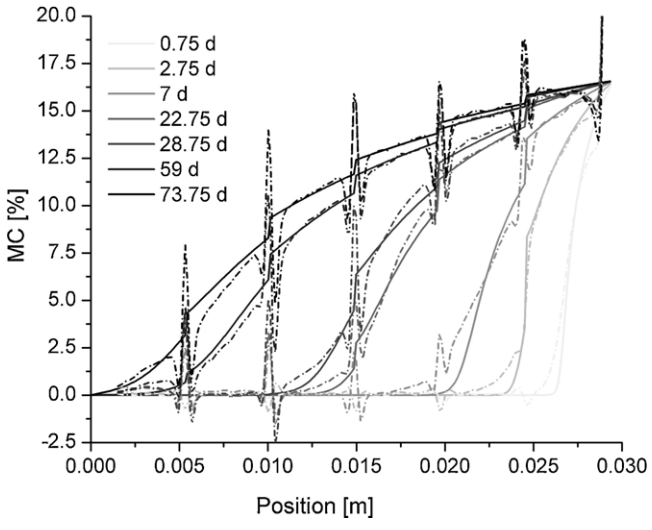

Fig. 15. Moisture profile in a multilayered wood sample over a period of 74 days determined by means of neutron imaging [24].

5.8. Thermography

This method uses the differences in heat conductivity of wood (e.g. knots, sound wood, intact glue joints, glue joints with voids, delamination). The thermography allows the detection of defects near the surface (approx. 1 mm), which allows for the detection of, for example, knots or the delamination of surface material (Fig. 17). Defects in the interior of the wood object can scarcely be identified due to the low heat conductivity of wood. Furthermore, the method necessitates the generation of a temperature gradient, e.g., initiation of heat flow in the sample by short illumination (lock-in thermography).

Fig. 16. Examples of coat thickness measuring using ultrasound. [26,27].

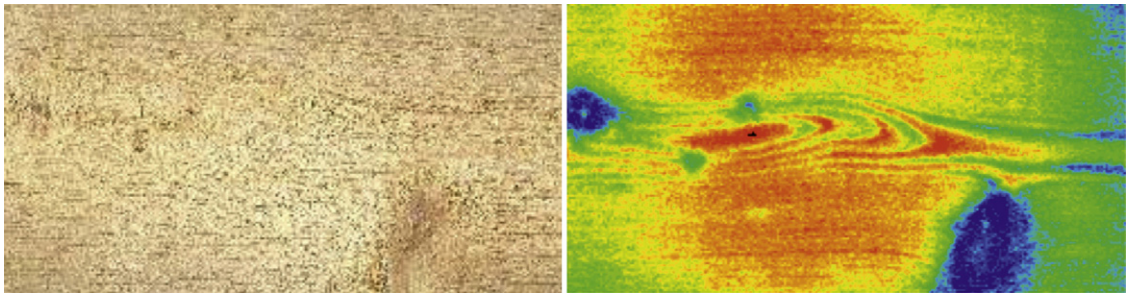

Fig. 17. Spruce wood sample with knots: photography (left) and thermography (right).

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