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*General Article*_________________________________ *Chapter -14*

NON-DESTRUCTIVE ASSESSMENT OF WOOD

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Abstract

Non-destructive evaluation (NDE) techniques are indispensable in comprehending the internal structure, health and properties of standing trees as well as felled logs without significantly compromising with their end use applicability. This scientific exploration encompasses a diverse array of methodologies, each contributing unique insights into the complex dynamics of tree anatomy and integrity. In response to the increasing need of assessing the health and properties of standing trees and felled logs, a number of robust tools have been developed in past years. These tools pave a way for assessment of wood properties with good accuracy without altering their end use applications. Non-destructive tools are becoming an important part of tree breeding programmes as destructive techniques are very time and money intensive process and trees with superior characteristics are required for future breeding programmes.Application of non-destructive techniques on tropical timber species is still in nascent stage unlike in the temperate regions where the technologies have become commercially operational (Chauhan & Sethy, 2016). This article, briefly describes the prominent NDE techniques, namely visual inspection, acoustic methods, Pilodyn testing, electric resistivity tomography, infra-red thermography, Rigidimeter, Ground Penetrating Radar (GPR), and X-ray Computed Tomography (CT) scanning, elucidating their principles, applications, and significance in the realm of arboriculture and forest sciences.

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Introduction

Visual Inspection

Utilizing visual inspection in combination with a comprehensive understanding of tree biology and biomechanics which helps in getting insights into the internal wood condition and facilitates diagnosis of potential failure (Mattheck & Breloer, 2010).The growth of tree is intricately responsive to its surroundings, functioning as a self-optimizing mechanical structure. The process includes formation of additional wood over affected areas (decay or damage) ensuring uniform mechanical distribution across its entire surface.Anomalies such as wound wood, trunk bulges or pronounced lower trunk flair surrounding collar region signify potential cracks decay or concealed cavities (Allison et al. 2020). Visual evidences such as fungal conks, crown retrenchment and open cavities further serve as an indicator of underlying decay and structural defects.While visual inspections offer valuable information for tree stability assessments, their scope is limited. For better understanding and to enhance the evaluation of trees, various non-destructive testing tools are available to researchers and forest managers. These tools serve as a window enabling a non-invasive exploration of wood, empowering humans to make impactful decisions based on a deeper understanding of potential issues.

Acoustic Methods

Acoustics have been used as a tool to measure quality of wood and wood products since long time. Acoustic tools could be utilised for evaluating the wood quality in standing trees, logs and various wood products such as lumber, composite panels etc. Utilisation of acoustic tools provides opportunities for planning, harvesting and efficient utilisation of timber. Other than this, it can be used in breeding and genetic improvement research programmes for early evaluation of trees for wood quality (Lenz et al., 2013). Acoustic testing mainly involves longitudinal stress waves, transverse vibrations and ultrasonic signals. Acoustic analysis works on the principle that the velocity of sound waves propagation depends upon wood density (Wang et al., 2004). Other than wood density, presence of defects such as cracks or internal cavities, decay significantly influence the acoustic velocity.

Mechanical sounding stands as a well-established forestry technique which involves percussions of a tree trunk with a wooden or rubber mallet, whereby the resultant drumming response serves as an indicator of an interior hollow. The phenomenon arises due to the attenuation or flattening of sound waves as they pass through a hollow transverse trunk section(Mucciardet al., 2011:Luley and Ellison, 2017:Luley and Ellison, 2018)**.**

Contrary to this, acoustic stress wave timers represent electronic portable device grounded in the principle that sound waves transverse wood at varying velocities contingent upon the density of tested wood (Wang et al., 2004). Notably, internal defects such as cracks or cavities augment the perceived time of flight of impact induced stress waves as they transverse the diameter of a tree trunk. In forest areas, stress wave timers offer a straightforward means of gauging the internal condition of the diameter path within the transversely examined section (Mattheck&Bethge, 1994).

It includes two accelerometers affixed to nails, spikes or screws with a shallow wood connection just beyond the bark portion on opposite sides of trunk, stress wave timers are usually linked by electric wires or cables to primary circuit board. For determining the acoustic velocity using time of flight method, probes (one transmitting and one receiver probe) are inserted into the tree trunk and signals are generated by tapping the transmitter end with a wooden or rubber hammerfor transmitting signals and measuring the time of travel between the two sensors for calculating the acoustic velocity. Dynamic modulus of elasticity (MOE_d) is strongly related to acoustic velocity (V) and MOE_d could be estimated using equation 1;

$MOE_d = \rho V^2$equation 1

Where, ρ is wood density and V is acoustic velocity.

Resonance method is also utilised for measuring MOE_dbut it can be used only when the test sample has two cut ends, thus making it unsuitable for estimating MOE_d in standing trees. A number of tools such as FAKOPP TreeSonic™ model, Microsecond Timer, Pundit 250 Arrayetc. are being used nowadays for measurement of acoustic velocity. These tools provide a suitable option for evaluating wood quality in both standing and felled trees.

Pilodyn

Pilodyn is a portable device used for assessment of density in standing timber and sawn timber.The tool was developed in Switzerland to acquire quantitative data on the degree of soft rot in wood. In a pilodyn, a spring-loaded striker pin is injected into the wood and depth of penetration is measured (Cown, D.J., 1978). Three different standard striker pins of diameter 2 mm, 2.5 mm and 3 mm are used in pilodyn. In standing trees, a small portion of bark is removed and striker pin is injected into the wood. This is why, the utilisation of pilodyn testing is more suitable for young trees having thin bark in comparison to old trees with thicker bark. The pin penetration depth is negatively correlated with the density of wood (Schimleck et al., 2019). Pilodyn testing is a less invasive technique as only a small hole (depending upon diameter of striker pin) is made into wood for assessment of wood density without causing any significant damage to the timber or tree. The drawback of pilodyn for assessing wood density lies in the fact that only outermost region is evaluated and therefore, it does not represent stem mean density.

Electric Resistivity Tomography and Infra-Red Thermography

Wood decay have a significant effect on the moisture content and electrolyte content properties of wood. The electronic resistivity serves as a viable metric for quantifying both properties, presenting an avenue for utilizing electronic resistivity tomography tools to discern the existence and magnitude of the internal decay of wood (Rust, 2000).Additionally, aberrant or compromised wood tissues, indicative of voids and deterioration can be identified through the measurement of thermal differences aided by an infra-red camera (Vidal 2019). The presence of defects disrupts the internal energy flow, resulting in discernible surface temperature variations.

Rigidimeter

A rigidimeter is used for measuring stiffness in standing trees (Launay et al., 2000). The weight of instrument is approximately 18 kg. The instrument consists of two independent units. The first unit is a trunk bending mechanism whereas the second unit measures the resulting deflection. Normally, the centre of the device is placed at a height of 1.3 m above the ground and diameter of the tree trunk is measured at the same height.A aluminium beam of rectangular shape is used for application of the bending force. Two wide steel contacts located on both ends of the gantry, are used for fastening the device into tree trunk. A foot-operated hydraulic pump is used for generation of required pressure for bending the tree trunk and a digital sensor records the pressure with an accuracy of 10 N. The mean deflection of the tree trunk is then measured at an height of 1.3 m above the ground level by the second unit with an accuracy of 10 μm (Pâques and Rozenberg, 2009).

Ground Penetrating Radar (GPR)

Emerging during World War II era, Radio Detection and Ranging(RADAR) technology utilises radio waves for determining range, velocity and angle of objects. The RADAR system includes an antenna for facilitating wave transmission, a receiving antenna and a processor for analysing results. In urban forest areas, RADAR finds common utility in subterranean detection of root structures. As the transmitting antenna transverses ground level, RADAR signals encounter objecting reflecting back to the receiving antennas. This interaction allows the processor to ascertain the spatial coordinates within the observed areas. Particularly in the context of underground root systems, RADAR relies on signals predominantly reflecting off the moisture content in roots, which helps in processing the estimation of root locations along entire soil horizons (Booty, 2018). Researchers have successfully applied this technology to investigate the root distribution and assess the impact of root infrastructure within the urban forests. (Bussuk et al., 2011: Butnor et al., 2009).

Ground penetrating radar (GPR) extends its application to living tree trunks, with findings indicating that the accuracy of GPR is contingent upon tree shape regularity and diameter. Notably, irregular shapes and smaller diameters pose challenges to GPR precision (Wu et al., 2018). Developments in GPR output have empowered the discrimination between voids and moisture pockets (Wu et al., 2019). Recent researches endeavours aim to refine the utilization of GPR for wood rot detection showcasing the continuous evolution and expansion of RADAR technology within the arboriculture studies (Senalik, 2017).

X-ray Computed Technology Scan

X-ray computed tomography (CT) scanning, a non-destructive testing modality, furnishes 3-D insights into internal heterogeneous structure of any object. Pioneered by A.M. Cormack and G.N. Hounsfield in the 1970s, CT scanning has evolved into a standard methodology in both medical and material sciences (Hounsfield, 1980). Established by

Johann Radon in 1917, this technology is rooted in the mathematical framework (Radon, 1986) which demonstrated the reconstruction of digital images through a comprehensive set of physical variable projections. This technology utilises ionizing radiations (X-ray or gamma ray). This methodology capitalises on the physical principle of absorption of high energy proton during travelling path through the testing material.Medical CT scanners are predominantly based upon the photoelectric absorption for attenuation. In case of wood, attenuation is primarily influenced by the Compton Effect, demonstrating proportionality to wood mass density. Variations in the density of wood is generally attributed to the distribution of anatomical structures and moisture content in the cell lumen and cell walls in the form of free water and bond water respectively.

The Nobel Prize winning observation of Arthur HollyCompton in 1927 formed the basis for understanding attenuation, highlighting the decrease in energy (resulting in increase of wavelength) of X – rays or gamma rays upon interaction with the material. The degree of energy attenuation is calculated by subtracting the number of transmitted photons at the receiving sensor from those generated at the initiation source. This calculation depends on the density, material thickness and mass attenuation coefficient(Hounsfield, 1980).

The calculation of attenuation coefficient has been elucidated in equation below:

$\mu_{rel} = 1000 \times (\mu_{material} - \mu_{water} / \mu_{water} - \mu_{air})$equation 2

Hounsfield Unit (HU) or sometimes a CTnumber is a term used for relative attenuation coefficient, μ_{rel} and is strongly correlated with bulk density. HU value of 0 and −1000 represents the density of water (1.0 g/cm3) and air respectively.

Some non-destructive methods with respect to wood properties have been described in the table below.

Table 1: Summary of Non-Destructive Testing Methods for Wood (Adapted from Zielińska & Rucka, 2021)

Criteria	**Methods**
Density	Ultrasonic, X-ray, Drilling, Electromagnetic, Pilodyn
Modulus of Elasticity	Ultrasonic, Resonance, Rigidimeter, Silviscan
Layer thickness measurement	Optical, Electromagnetic Methods
Moisture Content	X-ray, Electromagnetic Methods
Cracks	Ultrasonic, Acoustic Emission, X-ray, Thermography, Visual Inspection
Inhomogeneity	Ultrasonic, Acoustic Emission, X-ray, , ElectromagneticMethods, Thermography, , Visual Inspection
Deformations	Optical Laser, Acoustic Emission, Visual Inspection
Decay	Ultrasonic, X-ray, Thermography, Visual Inspection
Failure	Acoustic Emission, Ultrasonic

Conclusion

`The concept of non-destructive evaluation (NDE) is firmly entrenched in the wood science research field, denoting a process wherein specific properties of a material are tested without causing damage or altering its ultimate utility. While it can be contended that methodologies such as micro-drill testing, acoustic testing, and electrical resistivity tomography may inflict wounds in the bark or wood, and even tensioning through static/dynamic pull testing might stretch or rupture wood fibres, the prevailing consensus is that these techniques, on the whole, leave the tested tree minimally affected in terms of damage or alteration to its end-use capabilities. Consequently, these methods are generally acknowledged as non-destructive evaluation techniques suitable for application in the urban forest.Among the repertoire of techniques discussed in this article, including visual inspection, single path and multi-sensor acoustics, micro-drill resistance tests, and static/dynamic pulling tests, arborists and urban forest managers commonly employ these methodologies. Their popularity stems from their cost-effectiveness within practitioners budget constraints, coupled with a well-established scientific foundation and the availability of diverse manufacturers and equipment distributors.The evolution and widespread adoption of non-destructive testing tools and methodologies have played a pivotal role in enhancing the overall health and vitality of the urban forest. This progress marks a significant stride towards sustainable forestry practices and the preservation of urban green spaces.

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