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Section 2 **Test Methodology and Assessment**

Non-destructive evaluation of wood decay

Jan Van den Bulcke, Imke De Windt, Nele Defoirdt, Joris Van Acker

UGCT (University Ghent Centre for X-ray Tomography) - Laboratory of Wood Technology, Ghent University
Department of Forest and Water Management, Faculty of Bioscience Engineering
Coupure Links 653
BE-9000, Ghent, Belgium

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IRG SECRETARIAT
Box 5609
SE-114 86 Stockholm
Sweden
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Coupure Links 653
BE-9000, Ghent, Belgium

E-mail: Jan.VandenBulcke@UGent.be; Imke.DeWindt@UGent.be; Nele.Defoirdt@UGent.be; Joris.VanAcker@UGent.be

ABSTRACT

Evaluation of wood decay is often prone to subjective assessment. Standard rating scales are based on human perception of decay, often in addition to weight loss measurements. Especially the assessment of graveyard specimens or other long term testing material that has to be monitored regularly on a non-destructive basis, is challenging. In this paper two techniques are presented that can deliver extra insight. The first technique is based on the analysis of the resonance frequencies of the material. It is very fast and only minimal sample manipulation is required. Instantaneously, an approximation of the modulus of elasticity (MOE) and damping are obtained that can be followed during degradation. The technique is applicable in the field. The second method requires an X-ray tomography scanner, but enables a three dimensional view on the internal structure of the sample and accompanying degradation. It is not applicable in the field but can give a very interesting view on possible degradation patterns. Both methods can not only assist in non-destructive assessment, but can possibly best serve as early decay detection techniques and give more insight into the rate and modes of degradation.

Keywords: non-destructive, decay, X-ray tomography, resonance frequencies, damping

1. INTRODUCTION

It needs no explanation that long-term assessment of materials is an important tool in wood research. In-service performance prediction is the goal of many laboratory based testing and field trials, yet outdoor set-ups are the eventual benchmark. In-ground tests for instance can last for several decades and need to be assessed on a regular basis. They are of crucial value for proper evaluation of the durability of natural wood species, decay resistance of preservative treated wood and modified wood or from wood-derived products that are to be used in use class 4 (UC4; ISO 21887, 2007). The standard procedure for evaluation is based on a subjective rating given to the samples by an expert. These values are trustworthy, yet rough estimates of the actual state of decay. Several researchers therefore have been searching for a method to quantify the degradation in an objective way, more specifically by linking the visual criterion with strength or stifness (Grinda and Schöller, 2005a,b; Edwin and Ashraf, 2006). In addition, Van den Bulcke et al. (2010) elaborated on the incorporation of statistics in the analysis of visual ratings of graveyard tests. In all, incorporating sample variability in combination with objective criteria paves the way for a sound scientific basis of long term assessments. It is believed that by increasing both objectivity and sensitivity, service life prediction can boast quantitative data and failure can be detected in an earlier stage. This is certainly not limited to in-ground testing but also applicable to the approach as elaborated by Brischke and Rapp (2008). In this paper two techniques are evaluated as tools for objective characterization of the decay rate of wood specimens tested in in-ground contact. The first tool is the Resonalyzer, a measurement device allowing the determination of material parameters, more specifically the modulus of elasticity (MOE) through measured resonant frequencies of the stakes (De Baere et al, 2007). By simple analysis of the original signal, additional criteria such as damping can provide extra assessment when evaluating decay. The second technique is X-ray tomography scanning, which enables non-destructive visualization of the wood structure (Van den Bulcke et al., 2009). With this device density and density differences can be measured (Macchioni et al., 2007; De Ridder et al., 2011) at micro-scale. This non-destructive method allows to monitor the variation in density and thus the degree of decay in time. Furthermore, visualization of the internal structure enables assessment of the decay rate underneath the wood surface as well as the porosity induced by fungal attack, yet the influence of water on imaging can be both an advantage and a disadvantage.

2. EXPERIMENTAL METHODS

In 2006 a graveyard test was set-up on the outdoor field in Ghent at Ghent University, Laboratory of Wood Technology. More than 30 wood species are tested in-ground, sawn to dimensions 2.5 x 5 x 50 cm^3. Of these 30 wood species, 12 species were selected: sapwood, heartwood and CCA-treated sapwood of Scots pine (*Pinus sylvestris*), spruce (*Picea abies*), Siberian larch (*Larix sibirica*), European larch (*Larix decidua*), Douglas fir (*Douglas menziesii*), European oak (*Quercus robur*), chestnut (*Castanea sativa*), meranti (*Shorea* spp.), padouk (*Pterocarpus soyauxii*), afzelia (*Afzelia bipindensis*), movingui (*Distemonanthus benthamianus*) and moabi (*Baillonella toxisperma*). The first tool, for determination of the MOE non-destructively, is the analysis of the resonance frequencies using the Resonalyzer. Figure 1 shows the set-up schematically. The sample is suspended on 2 nylon strings, the accelerometer is glued in the middle and with a hammer a mild tap is given and the damping is measured as a function of time. This time spectrum is Fourier transformed to the frequency domain and the eigenfrequency of the resonant mode is determined. Using this frequency and the dimensions of the stake, the MOE can be calculated.

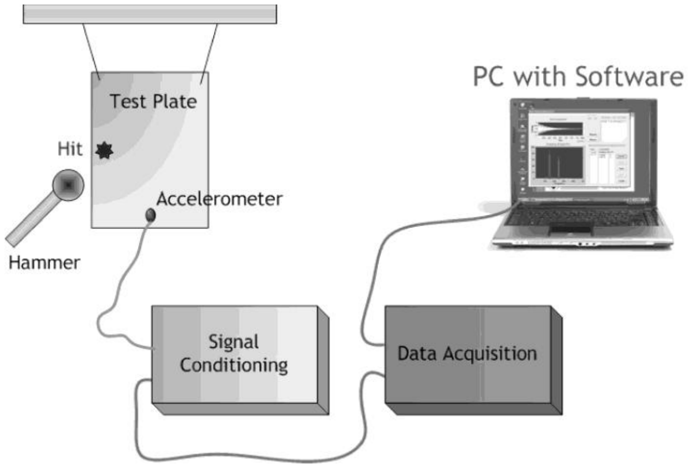

Figure 1: Schematic lay-out of the Resonalyzer.

For all specimens, the full frequency domain spectrum was recorded, as illustrated in Figure 2. This amplitude spectrum was inverse transformed to the time domain in order to obtain the impulse response function. The damping of the stake was then calculated by fitting an exponential to the decreasing maxima: $y = a \exp^{-bx}$ with b being the damping. This damping parameter might also be of use when evaluating the decay rate of the stakes.

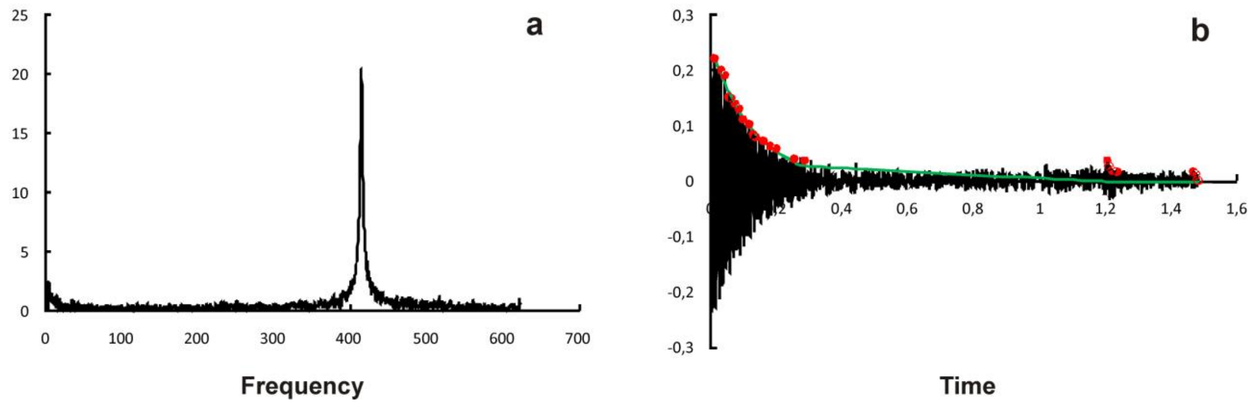

Figure 2: Frequency domain (a) and time domain (b) with impulse response function; red dots indicate the found maxima with the least squares fitting of a negative exponential to obtain the damping factor.

The damping factor, density, visual rating and MOE were used in a straightforward principal component analysis of the normalized values in order to get a view on the contribution of each parameter to the variance found in the different stakes.

Further, a selection of these stakes was scanned with the X-ray tomography scanner of the UGCT (University Ghent Centre for X-ray Tomography). The scanner is similar as the one described in

Masschaele et al. (2007) and Van den Bulcke et al. (2009) and has a generic CT scanner control software platform (Dierick et al. 2010). This device is a multi-resolution scanner, consisting of an 8-axis motorized stage combined with two X-ray tubes and two X-ray detectors, specifically designed to allow very high resolution scans as well as scans of larger objects. This set-up can scan small samples with low or high attenuation as well as large samples (up to 37 cm in diameter). Two specimens are mounted in a sample holder and scanned using helix tomography. In helix scanning mode, the samples rotate and at the same time make an upward movement, describing a helical trajectory. A standard set-up for helical cone-beam tomography is given in Figure 3, which is very well suited for elongated objects.

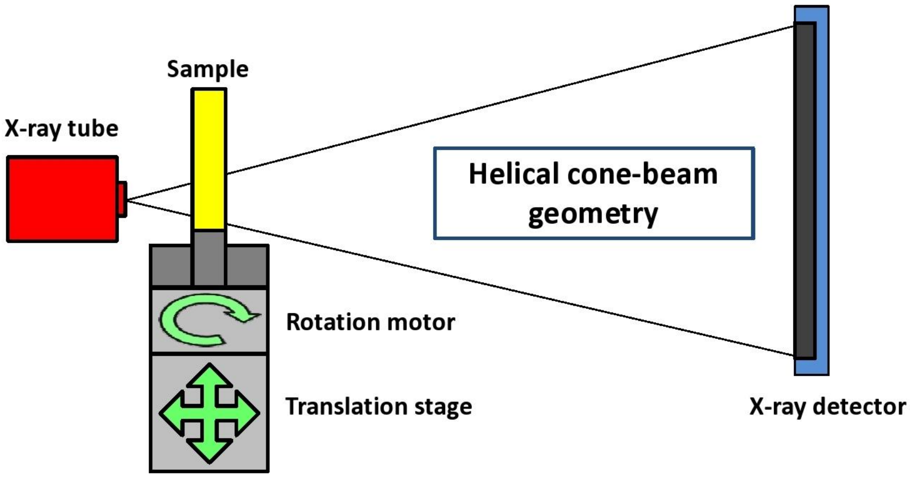

Figure 3: Typical high resolution set-up for helical cone-beam tomography. The long sample both rotates as well as makes a z-movement, as such describing a helix trajectory through the cone-beam shaped X-ray.

An average scan requires approximately 4 hours. Reconstruction of helix scans is done using the Octopus software package, a tomography reconstruction package for parallel and cone-beam geometry (Vlassenbroeck et al. 2007), including the helix algorithm implemented on the GPU. Reconstructed volumes take up approximately 1 GB with a voxel pitch of circa 122 µm. The total length of the scan is 15.5 cm, comprising that part of the sample located above and below ground level.

3. RESULTS AND DISCUSSION

Table 1 summarizes the different wood species under test, their average density, MOE, and damping factor when the calculation of the latter was feasible.

Table 1 Summary of MOE, density and damping factor for the different wood species

	# samples	**Visual rating**		**Density**		**E-modulus (Pa)**		**Damping**	
		average	stdev	average	stdev	average	stdev	average	stdev
Moabi	5	1,0	0,0	1050	58	1,79E+10	2,59E+09	-1,60	0,29
Padouk	5	1,0	0,0	834	63	1,32E+10	7,85E+08	-2,08	0,34
Siberian Larch	5	1,5	0,4	925	32	1,09E+10	1,28E+09	-1,91	0,22
Movingui	5	2,0	0,6	741	42	1,06E+10	3,12E+09	-1,62	0,57
European larch	2	3,0	0,0	710	59	9,61E+09	1,26E+09	-1,94	0,47
Afzelia	4	1,3	0,5	944	55	9,33E+09	2,98E+09	-1,21	0,31
Meranti	4	3,5	1,0	560	33	8,44E+09	3,11E+09	-1,43	0,43
Douglas	5	2,4	0,5	607	85	7,57E+09	2,24E+09	-2,24	0,12
CCA pine	5	2,0	0,0	530	75	7,38E+09	1,66E+09	-1,72	0,38
Pine heartwood	4	2,9	0,3	735	63	7,05E+09	8,08E+08	-1,54	0,22
Spruce	3	3,0	0,0	551	10	6,72E+09	1,46E+09	-1,83	0,19
Oak	5	2,3	0,4	746	36	6,58E+09	1,66E+09	-1,75	0,30
Chestnut	4	2,9	0,3	580	35	5,57E+09	7,53E+08	-1,60	0,32
Pine sapwood	2	3,0	0,0	775	46	3,72E+09	1,99E+09	-1,64	0,16

Clearly, density of some samples is high due to a high moisture content. A principal components analysis shows the importance of the various parameters (Figure 4).

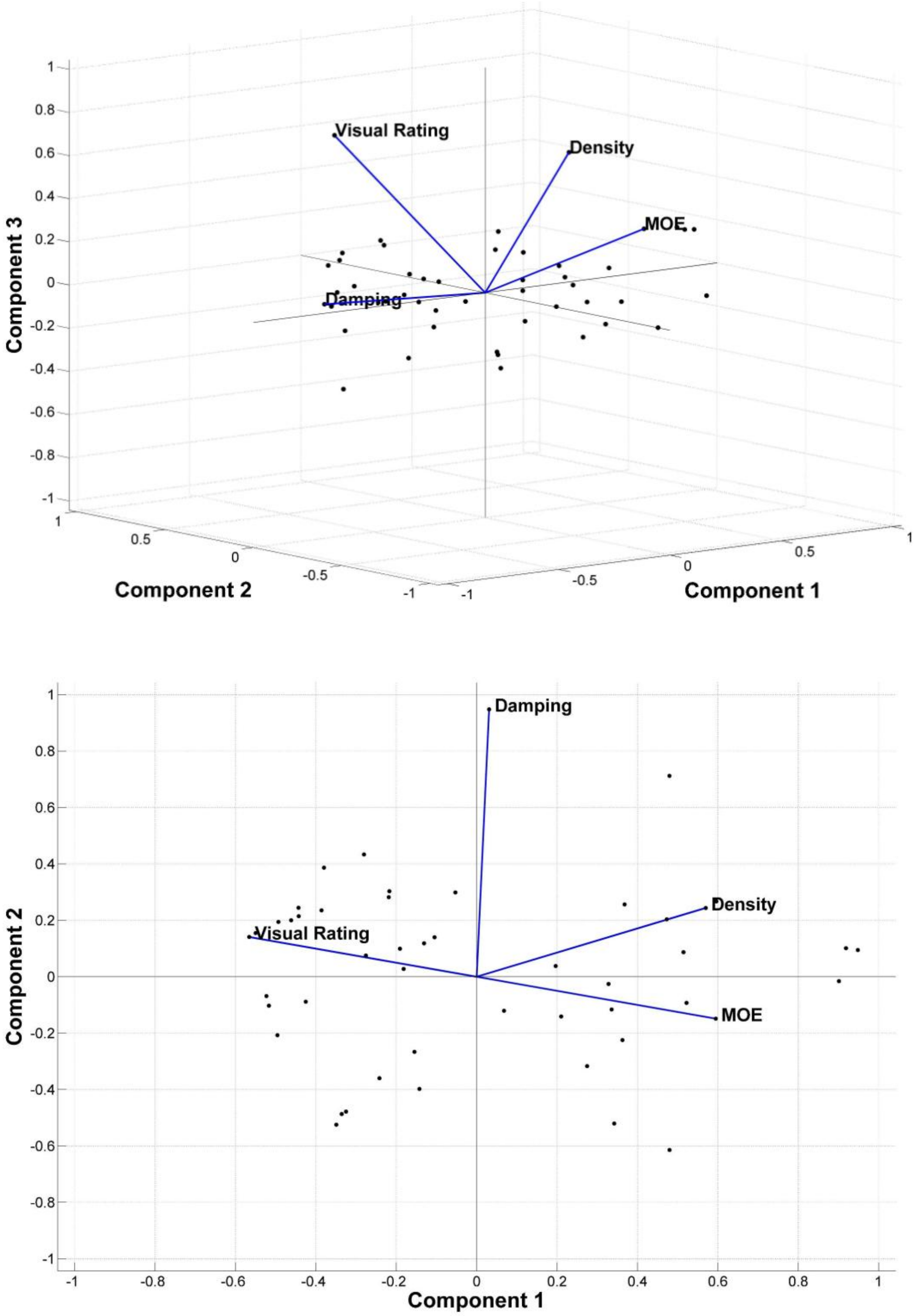

Figure 4. 3D (top) and 2D (bottom) plot of the principal component analysis on visual rating, MOE, density and damping.

The first three components explain more than 93% of total variation in the sample population. Obviously, visual rating is inversely related to MOE, whereas density has extra value in explaining the variability of the samples. The damping factor as calculated by fitting a negative exponential function to the impulse response data apparently has an important role in explaining the variation according to component 2. It should be stressed of course that interpretation of the data of both MOE and damping should be done with care as the measurements are performed on the complete stake, whereas degradation is mainly situated at one half of the sample. Therefore the measured

MOE and density are a mixture of relatively sound wood and degraded wood. In order to map local properties, one should use a laser scanning vibrometer. In addition, an effect that will become very clear on the tomography scans, is the influence of moisture in the samples.

A compilation of images obtained by X-ray tomography scanning are shown in Figure 5 for Siberian larch and meranti.

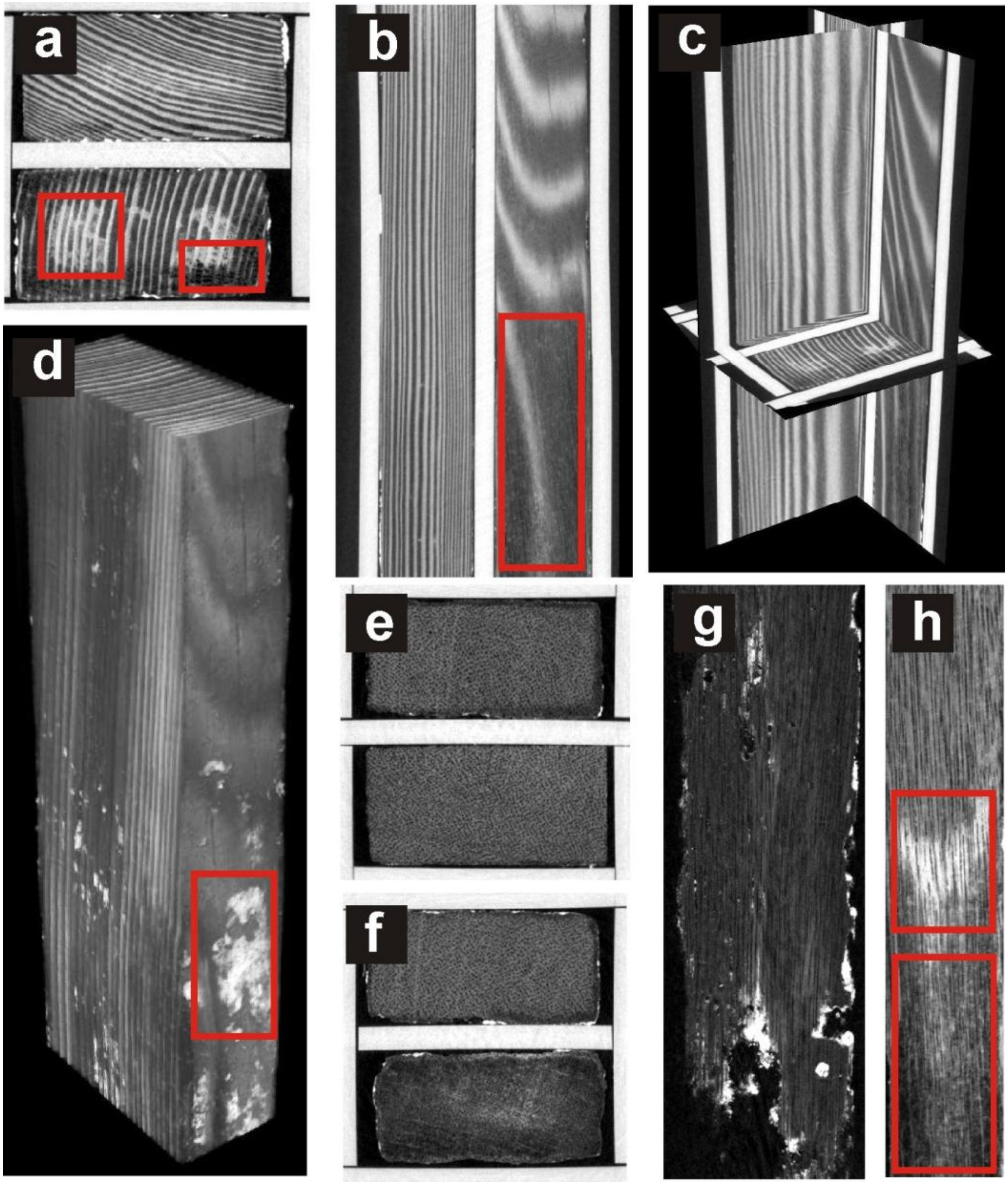

Figure 5: X-ray tomography scans of Siberian larch (a to d) and meranti (e to h): (a) Tv view on two specimens with indication of moisture (white patch in the middle of the specimen) inside the wood specimen and a zone with severe attack; (b) Tg and Rd view on the same specimens, with indication of the zone of attack; (c) orthogonal slices through the specimen; (d) 3D view of one of the Siberian larch samples with delineation of soil adhering to one of the sides; (e) on top a better performing specimen, which is more clear once a cross-section underneath ground level is chosen (f); (g) sectioning at one of the edges, showing soft-rot attack and soil; (h) at the bottom of this cross-section attack is clearly visible and the demarcation between an attacked zone and a (not yet) decayed part of the stake is formed by water (brighter zone in the middle).

These images once more underline the importance of X-ray tomography scanning for wood research. Specimens can be sliced and examined in all directions and one can obtain a clear view on degradation patterns. Several features are noticeable: the difference between the two Siberian larch samples (Figure 5), clearly demarcated earlywood and latewood zones, severely attacked patches of wood for Siberian larch, high density soil inclusions at the edges of the samples and water inclusions. Figure 6 shows a specimen that was scanned half an hour after removal from the test field (image at the left), while the image at the right is from the same specimen but scanned after 3 days. Clearly, the moisture restricts the image quality while after drying image quality improves. By differential imaging the determination of the moisture content and drying might also be an option for the assessment of the stakes, albeit that complete drying of the samples can be baleful for fungal growth. Yet, the amount of moisture and the distribution can also be taken into account when assessing the current and especially the evolution of decay.

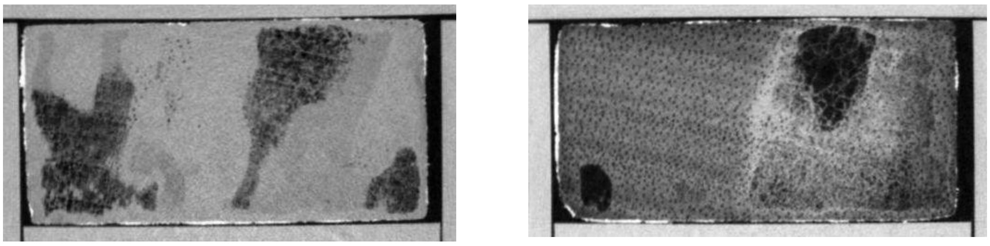

Figure 6: Before (left) and after (right) drying. Only the severely attacked zones are free of water simply because the wood material is no longer present.

Apart from the quantitative evaluation of the samples based on the reconstructions, calculation of the density differences is another option, yet with keeping in mind the influence of moisture. As elaborated in De Ridder et al. (2010), microdensitometric profiles can be obtained for Pressler cores, but more research is needed to make this technique generally applicable. The values as mentioned here therefore should not be considered as absolute densities but approximations, yet

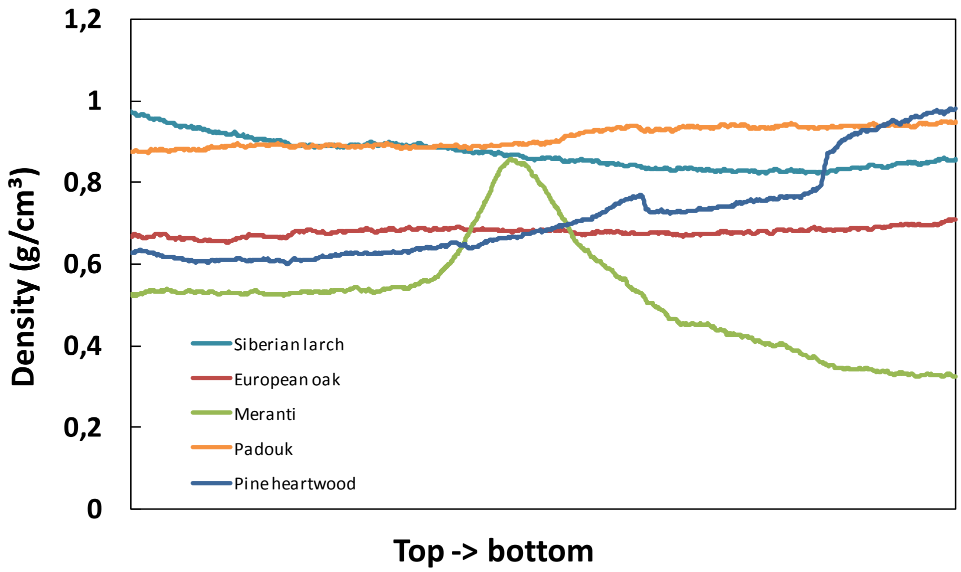

Figure 7: Density profiles through the samples from top to bottom.

these values are comparable as all scans are performed in exactly the same way. In Figure 7 the absolute density is given as calculated within a rectangular area on each cross-section from top to bottom, i.e. from above to below ground level for a selection of wood species.

Clearly, density changes can be ascribed to moisture and decay. For drier samples such as Siberian larch, the decay is very clear. This can be used as a measure for the decay rate. For meranti, the same is true, with a distinct peak of water at the zone between decayed and more or less sound wood. For padouk and very clearly for pine heartwood, water absorption caused an increase in density. On average, the density correlates quite well with the measured density. Ideally, with image processing the entire volume should be segmented and used to calculate the cross-sectional area, taking into account the original cross-section. As such also the amount of material that has been removed by fungal attack can be calculated as a decay rate. This will be incorporated in future work.

4. CONCLUSION

The Resonalyzer can be a helpful tool for fast assessment of long-term outdoor test specimens in in-ground field tests, complementing the visual rating given. The damping factor is only one of the parameters that can be calculated from the impulse response function and the derived amplitudes in the frequency domain. X-ray tomography scanning obviously gives a clear view on the internal structure and decay pattern of the samples, yet image quality can suffer from the moisture present. Nevertheless, the reconstructed volumes offer many opportunities for qualification and quantification of the wood structure, decay and moisture. In order to obtain optimal results, samples should be scanned before the start of the test to be able to visualize the changes that take place in the form of aforementioned parameters. Therefore these modalities will be further put to the test to see whether they can give the added value presented here. Obviously, this approach could deliver valuable input data for decay modeling and service life prediction models, and this is not only not limited to soft rot decay only.

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