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COMBINE USE OF NDT/SDT METHODS FOR ASSESSMENT OF STRUCTURAL TIMBER MEMBERS

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Methodology and protocols for routine assessment of wooden members with spectroscopy

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Introduction

Nondestructive testing (NDT) methods find a particular place among analytical methods used for structure assessment due to the limited amount of required sample, or in case of portable instruments possibility of performing measurement directly on-site. Unfortunately many of instrumental methods, even possessing plenty of advantages, are rarely applied on-site due to the lack of standardized procedures.

Infrared spectroscopy, in both near and mid ranges, is a well known technique with a great potential for chemical characterization of materials. It is useful for identification of various organic compounds, on the base on their selective absorption of radiation in the infrared region. As an effect of this phenomenon, the infrared radiation reflected from the surface can be used for estimation of the physic-chemical structure of the surface. Several researchers are focused on the evaluation of physical and mechanical properties of wood or estimation its degradation level. The objectives of this research are to highlight potentials and limitations of proposed techniques and to provide list of requirements for correct implementation of spectroscopy in routine assessment of wooden members.

Strength and limits of IR spectroscopy

Traditional infrared (IR) technique is used to analyze solid, liquid or gases by means of transmitting the infrared radiation through the samples. The Attenuated Total Reflectance (ATR) allows measurement without necessity of complicated sample preparation and furthermore provides good spectral reproducibility. The advantages of this technique are:

- little or no sample preparation;

- possibility to measure samples that are too thick or too opaque for traditional transmission IR;
- relatively fast measurement (minutes, depends on resolution);
- possibility of measurements solids, powders or liquids;
- possibility for determination of many components simultaneously;
- high degree of precision and accuracy;
- information related to chemical fingerprint;
- direct measurement with very low cost.

The restrictions of this technique are related to limited dimension of samples, pH constrains of used crystals and necessity of good contact between the sample and the crystal.

The FT-NIR technique is relatively simpler and possesses some very important advantages (in comparison to other analytical methods):

- simple sample preparation (to assure controlled MC and surface finish)
- non-destructive or semi-destructive testing (fast screening method applicable on site and more accurate estimation method with controlled samples in the laboratory)
- relatively fast measurement (seconds, depends on resolution);
- no residues/solvents to waste
- possibility for determination of many properties simultaneously
- high degree of precision and accuracy
- direct measurement with very low cost

The most important limitation of the FT-NIR is that the spectra are rather complicated and includes a complex overlapping of different overtones corresponding to vibrating functional groups. Consequently, data evaluation is necessary for proper interpretation and understanding of results. The resolution of the spectrometer is also limited, thus complicating the spectra interpretation even more. Moreover sensitivity to moisture variations, surface preparation, aging of surface affects measurement. It must be also highlighted that in case of assessment of timber structural members, with a certain thickness and length, sampling criteria must be defined so that global characteristics can be reliably inferred from a number of local (and superficial) measurements.

Methodology and protocols for routine assessment of wooden members with spectroscopy

Sampling and sample preparation

Representative reference sampling is essential especially when heterogeneous material such as wood is investigated. Precise sampling criteria must be defined in case of assessment of timber structural members. It has to be optimized depending on the structure topology, member size, state of preservation and due to the purpose of measurement. It has to be also highlighted that any measurement of mid or near infrared spectra may provide information related only to the local wood characteristics and is limited to the subsurface of the member. Sample preparation and presentation significantly affect reliability of presented techniques. Milling procedure, particle size, and quality of the solid wood surface influence the performance of the models to predict chemical properties. Recommendations regarding milled wood samples were presented by Schwanninger et al. [1]. Also the effects of sample presentation (solid or milled) affect reliability and quality of the models [2]. It is also important to minimize influence of temperature and relative humidity of the environment during measurement. Therefore, if it is feasible to take small amount of material from the member on site, it is highly recommended to condition it in climatic chamber prior spectroscopic measurements. Recently it is also possible to perform measurements directly on-site, especially with modern, portable instruments. Particular attention should be focused however on moisture content of measured wooden members and further correction, for proper data mining and interpretation.

Measurement procedure/sample presentation

Until recently, the preparation of samples to be measured with infrared spectrometers has been rather complicated; for example through solubilization of the sample or preparation of potassium-bromide (KBr) pellets for sample analysis (10 to 20mg of material). Fourier Transform Mid Infrared Attenuated Total Reflectance (FT-MIR-ATR) is a relatively new advancement of traditional mid infrared spectroscopy. It uses a phenomenon of absorbing infrared energy during reflection from the measured surface. This technique allows measurement of the wood powder or even wooden block surface without time consuming KBr sample preparation. Some instruments equipped with external reflectance module allow measurement of large objects without contact. This technique might be particularly

useful during on-site analysis by placing the instrument in front of the analyzed object. Fourier Transform Near Infrared (FT-NIR) spectroscopy offers even simpler measurement and its applicability for in-field measurement is good. Due to low absorption coefficients, bulk or thick samples of intact cellular structure can be measured [3]. Spectrometers equipped with fiber optic allow direct measurement of samples at a certain distance from the instrument (depending on fiber optic length). Use of fiber optic is most convenient approach for acquiring near infrared spectra. The reference light is emitted from the probe and reflected part of it is transmitted to the detector. The area of the detector varies and may cover from 1 to 20mm^2. As a result, the spectrum acquired is an "average" from the surface area corresponding to the probe having direct contact with measured object. No any extra pressure is required, even if the probe positing (deviation from the perpendicular placement) may influence the spectra outline. FT-NIR does not require sample preparation or hazardous chemicals, making it quick and reliable for quantitative and qualitative analysis. It is ideal for rapid material identification and is also a powerful analysis tool capable of accurate multi-component quantitative analysis. Recently hyperspectral system able to measure and characterize whole surface with high spatial resolution become more used. Hyperspectral images add a new dimension (spatial resolution) to the field of spectroscopy. They provide a means of accurately quantifying and locating constituent variation within the field of view of the camera, in addition to the identification and quantification of bulk constituents provided by integrating spectrometers. The measurement distance vary from millimeters up to meter and the spatial information is acquired directly by the spectrometer optics, by means of controlled positioning of the sample. The spectral band of hyperspectral camera may include various spectral ranges (UV, vis, NIR, IR) as well as Raman scatter. It provides the great possibility to characterize various physical-chemical properties of the surface with high spatial resolution.

Collection of representative spectra

The routine testing procedure for the measurements should be determined through a series of preliminary tests, in order to optimize the scanning procedure and improve the quality of results obtained from wood samples. Due to anisotropy and heterogeneity of wood, it is important to repeat measurements and average spectra. It is recommended to measure different samples on the corresponding/analogous points (for example on the radial plane). According to Tsuchikawa and Schwanninger [4] spectra collected from transverse and radial surfaces provide better prediction than those from tangential surfaces. The measurement location can be selected randomly; however, any visible abnormalities of wood surface (such as resin canal, knot or discoloration) should be intentionally omitted, unless the measurement of defect rate is intended.

Data evaluations

NIR absorption spectra are often complex and normally possess broad overlapping absorption bands that require special mathematical procedures for data analysis. In contrary MIR absorption bands are well-resolved, assignable to specific chemical components. Moreover the signal-to-noise ratio of NIR is poorer than that of FT-MIR-ATR and interpretation of spectra more problematical. However NIR spectra contain a lot of information related to hydroxyl groups linked to several chemical components, which, in case of wood, are very relevant also for the estimation of physical and mechanical properties of the material. Interpretation of spectra is very important and is highly recommended to include this step in routine analysis. Recently published works provides valuable information in regards of bands assignment [5-8]. Visual observation of spectra is also the easiest method to detect outliers caused by errors during measurement (not parallel position of fiber optic (in case of NIR) or incorrect contact between sample and crystal (in case of ATR). Spectra identification and qualification (quantitative analysis) can be done by comparing a sample spectrum to reference spectra of known materials (or in case of decayed samples with reference samples infested with various fungi). Quantification is done by using mathematical models and so-called multivariate data analysis (MVA): these approaches are generally referred as chemometrics. MVA techniques are statistical design tool for dealing with very large datasets, which allow more than two variables to be analyzed at once. Multivariate data analyses are usually divided into three groups: exploratory data analysis, regression analysis and classification models. Exploratory analysis (data mining), attempts to find the hidden structure in large complex data sets, examples are Cluster Analysis or Principal Component Analysis. Regression analysis and Predictive Models, such as Partial Least Squares Regression or Multiplicative Linear Regression, are used for developing the models from available data and predict desired response. Even if both spectral noise and reference method noise affect the accuracy and the precision NIR predicted values sometimes model based on the noisy reference data led to good results [9]. Classification Models (Cluster Analysis Test, Identity Test or SIMCA) allow separation of group of objects into one or more classes, on the base on distinguished characteristics. Figure 1 summarizes recommended protocol for routine assessment of wooden members with spectroscopy [10].

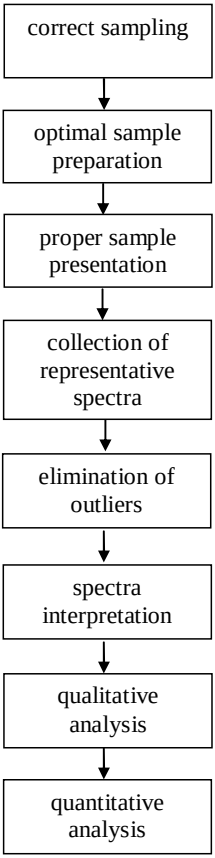

Fig. 1. Schema of proposed stages for wooden members characterization. Source: [10] modified.

Application of spectroscopy for assessment of wooden members

Spectroscopy allows understanding of chemical changes of the wooden material during various degradation processes. It allowed classification of decay type and prediction of modification of physical properties, as a consequence of the decay process. It has been also successfully applied for monitoring the weathering process of different wood species, understanding the weathering dynamic and estimating both exposure time and service life of wooden structures [10]. Reports related to characterization and evaluation of waterlogged wooden samples, both from archaeological site and recent wood during short term waterlogging are recently published [11-12]. Several researchers already proved applicability of infrared

spectroscopy for species recognition, prediction of moisture content, density, tensile strength, mechanical stresses, bending MOE and MOR [4]. In general, spectroscopy works with all wood species. Most of up-to-data prediction models reported in the literature are valid for a single wood species only. However, the development of generalized chemometric model suitable for several wood species is of great interest [9]. The important concern is related to the timber surface in use, including oxidation, ageing and/or weathering. As a consequence, chemometric models developed for one sample lot may not be functional for same wood samples, but processed with different preparation procedure. In such case, calibration transfer formula is necessary. It has to be mentioned, that spectroscopic measurements are related to the surface, therefore can not be straightly correlated with internal properties of the members. The solution is to combine sampling with other methods (e. g. radial coring for dendrocronological analysis or semi-destructive analysis) and acquire the spectra along the members depth (e.g. radial profile).

The development of electromagnetic (EM) wave-based methods, such as spectrometric techniques, imaging techniques, electric and optical methods, as well as the increasing availability of portable instruments, has opened up new perspectives for on-site characterization and monitoring of building materials. Moreover the trend for material characterization by using multiple sensors simultaneously has become well accepted. It is more favorable than a single sensor approach due to far better representation of the real-world cases. The speed of measurement is comparable with other NDT for decay detection, such as dynamic indentation (Pilodyn®) and infra-red thermovision, among others. The other challenge is however the correct interpretation of measurement data assuring integration/fusion of all indicators as the multisensory data is usually correlated with each other.

Practical application of spectroscopy for timber structure assessment provides very essential supplement to the typical information collected traditionally with standard procedures. Special attention is focused here to highlight potentials and limitations of proposed techniques and to provide list of requirements for correct implementation of spectroscopy in routine assessment. Up to now several researchers confirmed advantages of spectroscopy for evaluation of wood properties. However application of this technique for on-site wooden members inspection requires a proper definition of sampling criteria, according to the properties investigated, as well as prior preparation of dedicated databases of high precision reference values. Those are essential to build reliable, flexible and sufficiently generalized models. The method then might be a tool assisting experts in the estimation of reference material properties, and other relevant mechanical/physical characteristics, in a fast and repeatable way.

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