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

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Estimation of thermo-physical parameters of wood by thermal measurements

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Abstract

Thermal metrology primarily responds to three needs [1]. The first is mastery of manufacturing process in which a monitoring or an automated control solution is needed. The second is to highlight thermal effects in a system for which there is no obvious numerical solution (local heat transfers in huge system). The third responds to the evaluation of thermo-physical properties of materials and interfaces needs in order to know and to improve materials. This evaluation can add new fields of knowledge to numerical modeling of complex systems. The quantitative thermal analysis falls into this last category.

Introduction to thermal metrology

Thermal metrology is based on the exploitation of measurable physical quantities, i.e. temperature and heat flux, respectively expressed as kelvin (K) and watt (W) in the international system of units. In addition to temperature and heat flux, two others groups of physical quantities are defined: physical quantities linked to the material itself and physical quantities linked to its interface with environment or surrounding objects. Only temperature and heat flux can be directly measured via thermal sensors. Evaluation of others physical quantities needs to master the resolution of inverse problems.

Thermal analysis methods of thermo-physical properties of materials have the same basic protocol. First, temperatures and/or heat flux are measured with thermal sensors. Then, one or several thermophysical properties (e.g. thermal conductivity) associated with studied material are evaluated via the use of mathematical formalisms [2]. Finally, several thermophysical properties may be seen from previous ones (e.g. water content given by thermal effusivity [3]). Solid, granular, liquid, gaseous or whether phase change materials (PCM) [4] can

Table 1. Example of several physical parameters that can be determined from thermal analysis

Physical parameters	Determined by...		
	Direct measurement	The resolution of an inverse problem	Evaluation through others physical parameters
Temperature	x		
Heat flux	x		
Thermal conductivity		x	
Thermal diffusivity		x	
Thermal effusivity		x	
Specific heat			x
density			x
Water content			x
Convection coefficient		x	
Contact thermal resistance		x	
Surface radiative characteristics		x	
Enthalpy		x	
Viscosity			x
Porosity			x

Table 1 is given for a single material, but thermal methods can be extended to composite materials. It may be possible to have global information of a system while generally the purpose is to highlight the presence of thermal resistance inside the medium (e.g. poor adherence [5] or cracks). There are a lot of thermal methods because these cover a wide field of analysis :

- destructive (probes [6]) or non-destructive methods (infrared thermography, IRT [7]),
- local (studies on micro and nano-components [8]) or huge areas can be investigated (thermal Doppler for atmosphere analysis [9]),
- monitoring over time [10],
- methods can be used on laboratory or on site [11].

With regards to positive points, it should be pointed out that thermal methods are very widely used, adapted to many materials and have applications on site. The significant presence of these methods also involves the existence of a wide variety of sensors to meet the most varied individual needs and budgets.

However, although thermal methods are widely used, these have some limits. Disadvantages are related to the used of specific thermal method but it exists a common denominators:

- Thermal methods are usually slow as compared to others mechanical methods (Thermal diffusion effects),
- Absolute accurate temperatures (accuracy of about 50mK) are difficult to obtain,
- Global analysis. It is difficult to link information with a space discretization (anisotropy),
- Quantitative analysis usually needs thermal solicitations that can modified thermophysical properties of the medium.
- In spite of thermal sensors are steadily improving, heat flux measurement is still difficult.

To solve these problems, the use of coupled mechanical or optical methods with thermal method is the usually prescribed solution in order to determine in particular a thermophysical properties.

Thermal methods and wooden structures

As previously shown, there are a lot of thermal methods and it is not possible to provide an exhaustive list of them. Therefore, it was focused on thermal methods suitable for wooden structures. Wood is a porous material with a very complex microscopic architecture. Thermal methods usually employed consider wood as a homogeneous medium for a specific direction [12]. If on site applications should be considered, non-destructive thermal methods (NDTM) have to be retained and can be active or passive ones. If wooden structures can receive solar radiations (random solicitations), passive methods should be considered [13]. Out of this specific context, NDTM have to use artificial thermal solicitations in which a deterministic signal is used. Two kinds of method could be employed on laboratory or on site : thermal methods with contact and thermal methods without contact.

Thermal methods with contact: Guarded hot plate test (laboratory) [14], hot wire or hot plane (laboratory) [15] and the combined used of thermocouples and fluxmeters (laboratory and on site) [16] are widely used.

The principle of the procedure is based on the installation of sensors on the medium boundaries. Then, thermal solicitation (deterministic signal) creates a disturbance. Thermal sensors measure thermal response of the medium (temperature variation and/or heat flux). Global thermo-physical properties access (thermal conductivity, diffusivity and effusivity) is given by mathematical formalism (resolution of inverse problem) and depends on injected signal (step, sinus, ...).

These methods can be accurate and suitable for small sample with low rugosity at the sample surface in order to limit thermal contact resistance between sensors and sample [17].

It is recommended to work with thermal sensors to be able to measure temperature and heat flux with a minimal accuracy of respectively 100 mK and 1 W/m2. Wood samples have to be adapted to the sensors size. Measurement area of thermocouple is about one square millimeter but fluxmeters (plane sensors) have a measurement area ranging from 25 cm^2 to 400 cm^2. Wood samples will usually have a volume greater than 100 cm^3.

On site monitoring is often more difficult than carried out laboratory tests. So, another interesting recommendation is to create a database of thermo-physical properties of their own wood samples in order to easily specify limits of thermal methods carried out on site.

Methods without contact: It is without question that IRT is the predominant NDTM without contact [18]. It is a well-known method and applications are numerous [19-22], even though wood is often less studied than other building materials because of its complex thermal behavior.

IRT protocol is the same as active thermal methods with contact but instead of the determination of thermo-physical properties, the first objective is mainly to detect thermal contrast (directly or after image post-processing [23]). In wooden structures, defects usually detected are void, cracks or moisture [24].

Wood is a material with a low thermal conductivity, so, it is recommended that thermal solicitations last long enough to have a good thermal diffusion in the medium. For a study on first millimeters of a wooden structure, tests should last about ten minutes. For a deeper investigation (5 to 6 cm), tests can last more than two hours. Thermal solicitations have to be low in order to not disturb thermo-hydro behavior of porous medium [25].

Data analysis

Inverse methods are used to data processing. Numerical method is chosen according to the nature of injected signal and thermo-physical properties or thermal effect it needs to be determined. There exist temporal methods based on simplified description of thermal problem to solve (function series decomposition) or spatial and temporal interpolation (Finite Differences [26] and Finite Elements Methods [27]). Others methods are based on a frequency description of thermal problem as thermal quadrupoles methods [28].

Signal-like steps are usually used with temporal description to determined conductivity. To better characterize thermal behavior of wooden structures, more complex signals (sinus, sweep [29], pseudo-random binary sequence PRBS

[30],...) are mainly used. Thermal diffusivity and thermal effusivity can be so determined.

There is a good correlation between thermo-physical properties that can be directly identified (conductivity, diffusivity and effusivity) as well as some physical quantities such as water content [3] or porosity [31,32]. Correlation functions can be established to link on site measurements and laboratory data.

In summary, thermal methods can be used to determine thermo-physical parameters of wooden structures, other physical quantities (such as water content, porosity) and defect inside the medium (cracks, voids). Global on site thermal analysis (IRT) work fine but makes anisotropic properties of wood difficult to evaluate i.e. thermo-physical properties are known for a specific volume and not necessarily for a specific direction. Thermal methods are still attractive even in terms of preliminary structural analysis. However, a precise diagnosis needs association with other NDT methods (e.g. ultrasound [33]). Data fusion is in constant development and NDT methods collaborations have to be followed with attention.

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