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Characterization of density variations of historic timber structure by thermal methods

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Abstract

The aim of this paper is to define applicable principles and practises to monitor historic timber structures by means of thermal methods. Wood density has an important impact on mechanical properties such as modulus of rupture. It is necessary to study the pattern of variation in wood density to estimate timber structure sustainability. A database of several thousand of thermal behaviours of porous media were developed and compared with *in situ* thermal measurements. With an appropriate formalism based on thermal quadrupoles and the study of signals in frequential domain, variation density can be characterized for the first centimeters.

1. Introduction

Due to their cultural significance, historic timber structures need protection and preservation. These structures, wholly or partially in timber, are vulnerable. Humidity fluctuations, light, fungal and insects attacks cause material decay and degradation [1]. These disorders modify wood density, i.e. the amount of actual wood substance present in a unit volume of wood. Modulus of rupture, modulus of elasticity and compressive strength are linked to wood density. Variations of mechanical properties can so be evaluate through variations of density [2]. Historic timber structures with an high porosity need reinforcement. The diagnosis should be based on physical inspection and analysis, preferably, non-destructive methods.

At the surface of a timber structure (first millimeters), porosity can be high. Visual inspection (figure 1) is not able to determine density variation deeper in the medium. Destructive methods (e.g. the use of a core drill) are the easiest way to identify the porosity of part of a timber structure. However, in order to preserve cultural heritage, Non-destructive methods are most suitable for the purpose of diagnosis [3].

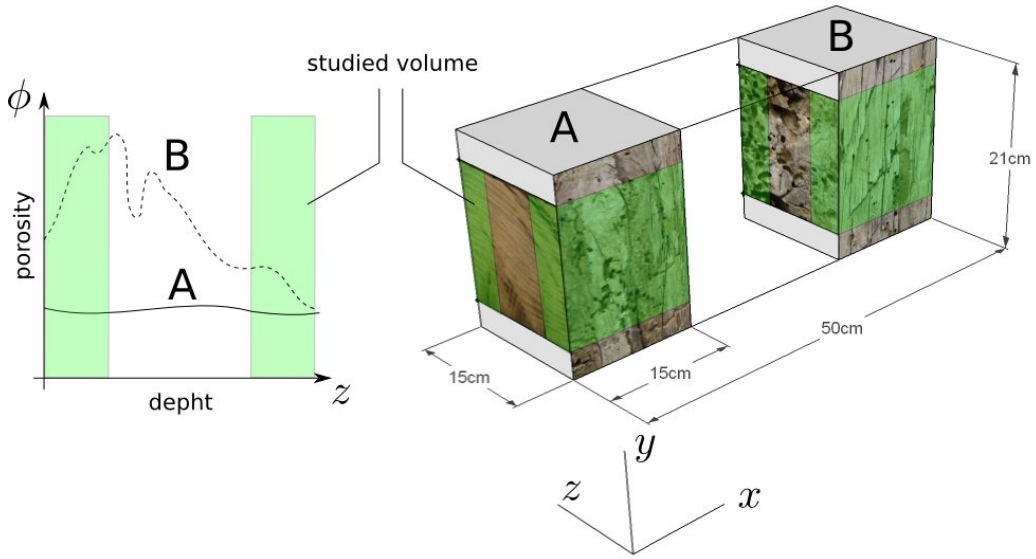

Fig. 1. *Comparison between two porosities variations in a single sample of wood and visualization of studied volume by active infrared thermography*

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2. Material and methods

2.1. Material

Initial experiments are made in laboratory. The figure 2 shows experimental device. A sample of wood (A) received thermal solicitations from two spotlights (C). Temperature evolution is measured by an infrared camera (B). A computer generates a sweep signal (F) sent to a generator (D) that control spotlights. Another computer (E) records infrared images form the camera (CEDIP – 80mK).

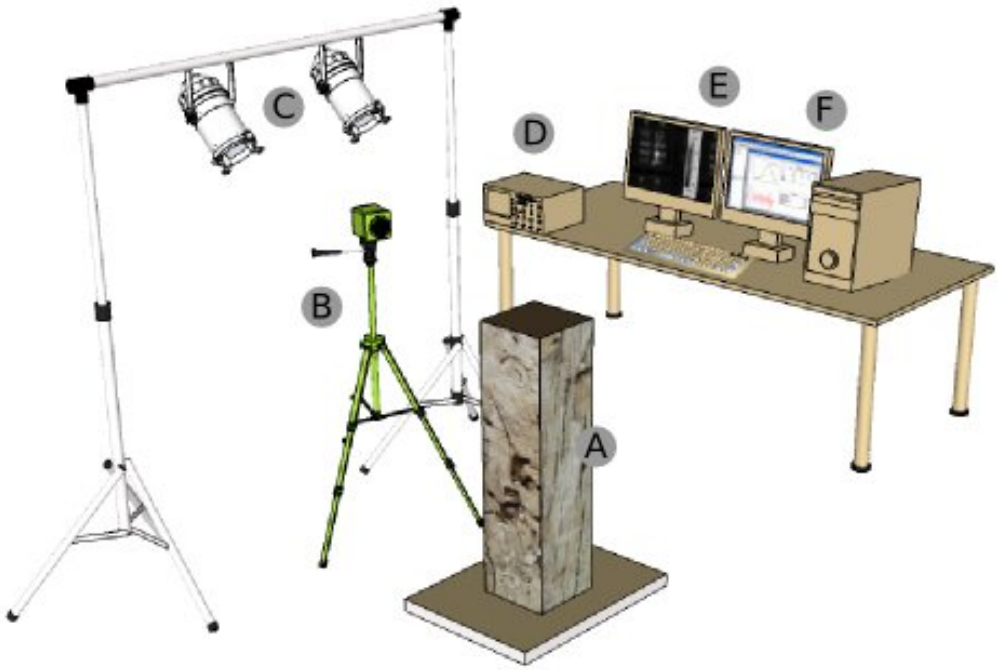

Fig. 2. *Experimental device*

2.2. Methods

At the beginning, a SWEEP signal is chosen [4]. The purpose of SWEEP signal is to give us enough information to have an accurate definition of the input thermal impedance of the sample. Frequencies are chosen in order to penetrate first centimeters of the sample until potential sound area depth is reached. In our case, main problem is that defect areas create thermal resistance and induce temperature elevations at the surface of the sample (fig. 3). Thermal response at the surface of a defect area hide information and data need to be processed. A temporal study is not suitable in this case. A better way to process is to work with frequential analysis to focus on specific frequencies.

With frequential analysis, signal is composed of magnitudes and phasis. The value of temperatures at surface of sample can be also not reliable. Rugosity at the surface of sample induces some emissivity variations. In this case, the better is to study phasis because it is less sensitive to emissivity variations [5]. This method is a good way to monitor on field with few parameters that can be controlled.

Injected SWEEP signal can be defined as follow :

$$S(t)=\frac{A}{2}[\sin\phi-\min(\sin\phi)] \quad (1)$$

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with

$$\phi = 2\pi F_{min} t + \frac{F_{max} - F_{min}}{2t_{max}} t^2 \quad (2)$$

t, time vector
F, frequency
A, amplitude of injected signal

SWEEP signal is used for thermal loads and temperature response is measured with an infrared camera (fig.4).

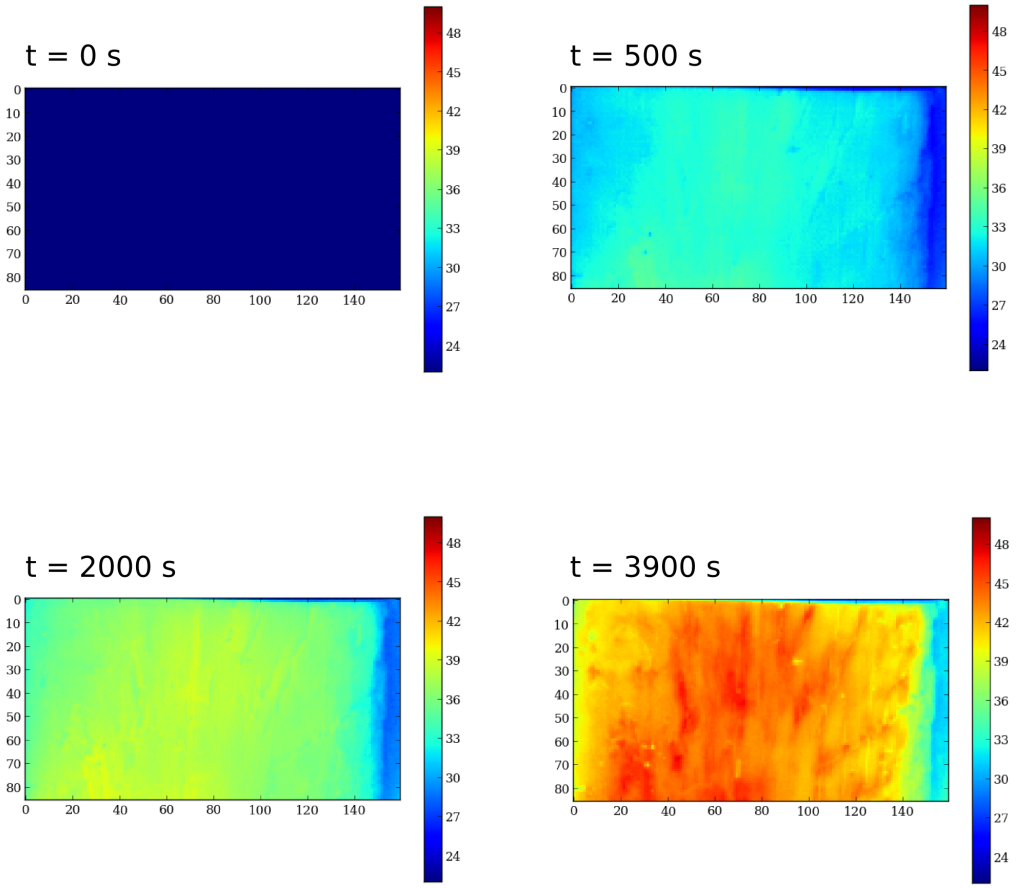

Fig. 3. Variation of porosity at surface of sample induces temperature elevation

Each image represents a matrix **im**[*ij*] in which *i* and *j* represent a pixel position. A 3D matrix contains all images information by time **imt**[*ijk*]. For each pixel, time evolution is extracted and his Fast Fourier Transform (FFT) is computed. θ and φ represent respectively the FFT of the surface temperature *T* and the heat flux *Q*. From infrared measurement, the input thermal impedance can be determined as follow :

$$Z_m = \frac{\theta}{\varphi} \quad (3)$$

and the phasis of the signal is defined by : $\Omega_m = \arctan\left[\Im\left(Z_m\right), \Re\left(Z_m\right)\right]$

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Thermal impedance represent the behaviour of the medium [5]. This is an information that can be compared to numerical model of thermal impedance (e.g phasis comparison) in order to identify some thermophysical properties. So, phasis is computed for each pixel and some frequencies. Results are input in a 3D matrix **P**[*ijn*].

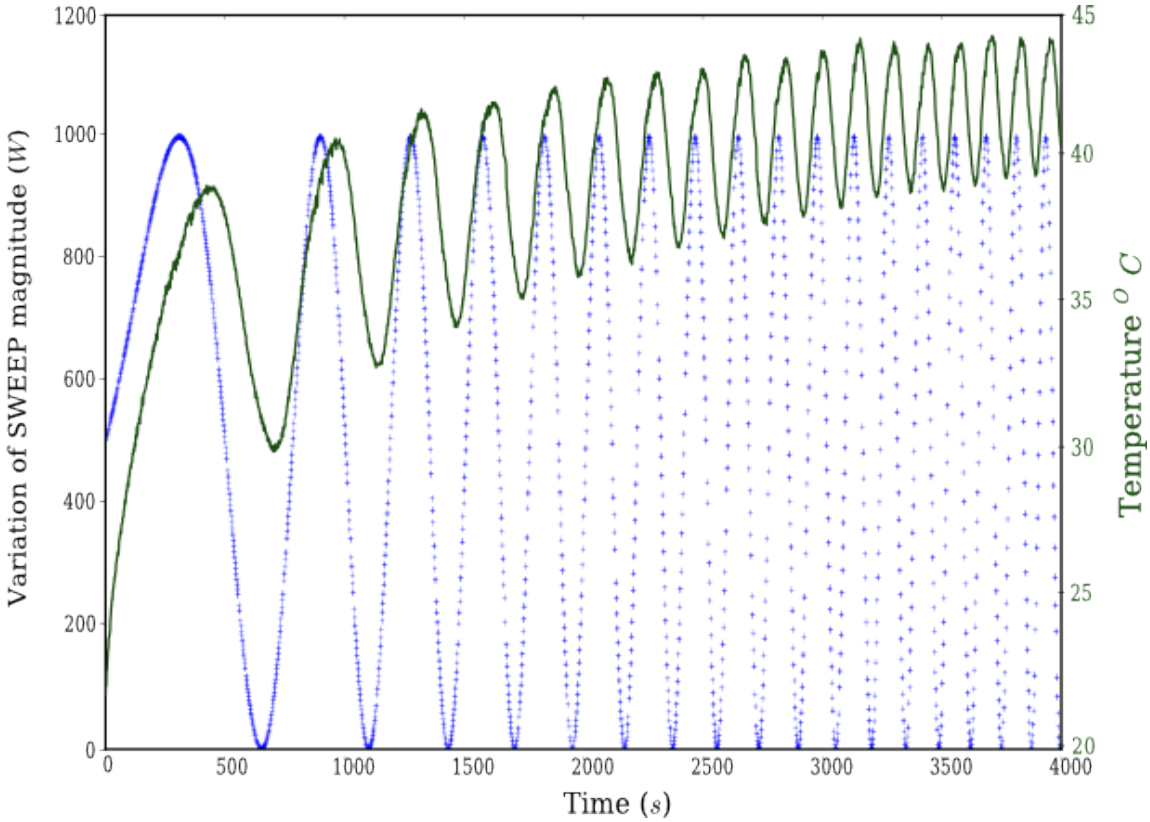

Fig. 4. Example of temperature response to a SWEEP signal at a known pixel

Then, measurements are compared to generated models. A wide range of thermal behaviours models is created. Models are the frequential temperature response to a sweep heat signal injected at the surface of a sample of wood made of several layers of different porosities. 1D physical models based on thermal quadrupoles formalism are used [6]. This formalism links input and output thermal quantities θ and φ by a matrix which represents the transfer function of a medium :

$$\begin{pmatrix} \theta_i \\ \varphi_i \end{pmatrix} = \begin{bmatrix} \cosh(\alpha) & \frac{1}{\beta}\sinh(\alpha) \\ \beta\sinh(\alpha) & \cosh(\alpha) \end{bmatrix} \begin{pmatrix} \theta_o \\ \varphi_o \end{pmatrix} \tag{4}$$

with

$$\alpha = e\sqrt{\frac{p}{a_w}} \quad \beta = \frac{1}{b_w\sqrt{p}} \tag{5}$$

e : thickness of the medium
a_w : thermal diffusivity of wood sample
b_w : thermal effusivity of wood sample
p : Laplace variable

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Thermal diffusivity and thermal effusivity depend on thermophysical properties, thermal conductivity k_w , density ρ_w and heat capacity c_w . These parameters can be defined as porosity function. To generate models, fractal description is used [7] :

$$k_w = \frac{0{,}5(1+\epsilon)^2 k_s k_f + \epsilon(1-\epsilon) k_f^2}{\epsilon(1-\epsilon) k_s + 2\epsilon k_f} \tag{6}$$

$$\rho_w = (1-\epsilon)\rho_s + \epsilon\rho_f \tag{7}$$

$$c_w = (1-\epsilon)c_s + \epsilon c_f \tag{8}$$

Consistent to the litterature, wood sample have porosity (ϵ) which can varies between 0,25 and 0,7. For a study concerning first centimeters, it is possible to give an expression of thickness e of a layer in the medium as function of porosity :

$$e = \frac{\epsilon}{15} - \frac{1}{60} \tag{9}$$

$$\epsilon = \epsilon_{min} + \frac{\epsilon_{max} - \epsilon_{min}}{2}[1 - \tanh(20\epsilon - \gamma)] \tag{10}$$

γ can takes values between 5 and 15 (fig. 5)

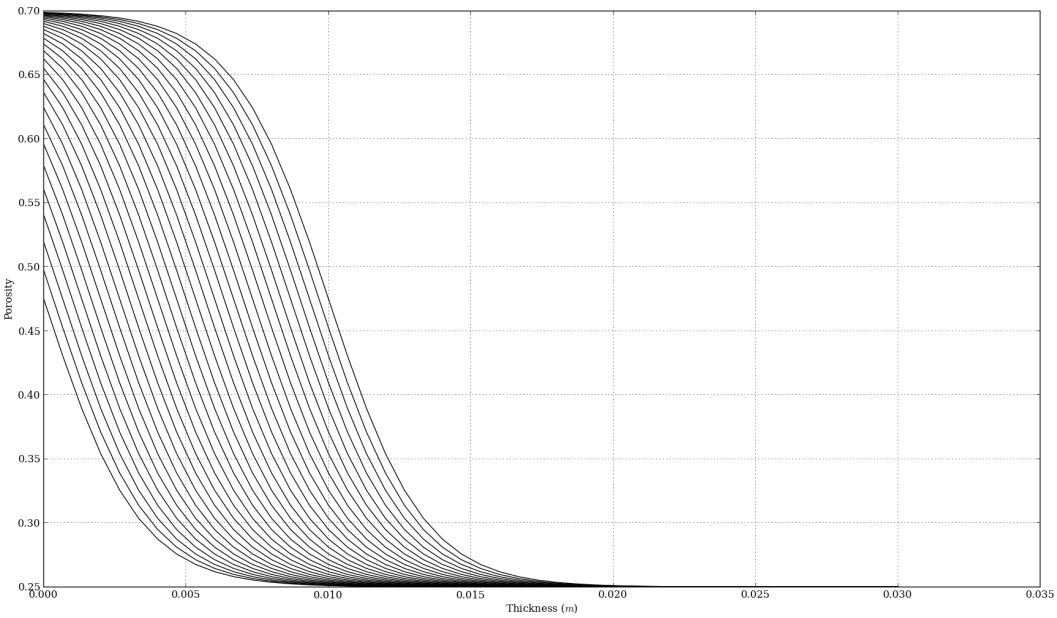

Fig. 5. Porosity variation as a function of depth for $\gamma \in \{5;8\}$

Values of thermophysical parameters used for model generation were taking according to litterature [8-9] (tab. 1)

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Table 1. *Thermophysical parameters used for model generation*

	Solid Phase			Fluid Phase	
	cellulose	hemicellulose	lignin	air	water
k	0,26	0,34	0,39	0,026	0,6
ρ	1500	1500	1225	1	1000
c	1500	1500	1300	1000	4185
[%]	50	30	20	66	34

Model generation is based on a discretization of sample geometry. For each thickness of a layer Δe, thermophysical parameters (a_w,b_w) can be determined as a function of porosity. Input and output thermal quantities are linked by a general matrix defined as follow :

$$M^z=\begin{bmatrix} M^z_{11} & M^z_{12} \\ M^z_{21} & M^z_{22} \end{bmatrix}=\prod_{k=1}^{n}\begin{bmatrix} \cosh(\alpha_k) & \frac{1}{\beta_k}\sinh(\alpha_k) \\ \beta_k \sinh(\alpha_k) & \cosh(\alpha_k) \end{bmatrix} \tag{11}$$

Output quantities can also be redefined if sample is considered as a semi-infinite medium. Output temperature is linked to heat flux by output thermal impedance :

$$\theta_o = Z_\infty \varphi_o = \frac{1}{b_w\sqrt{p}}\varphi \tag{12}$$

That suggested that :

$$Z_i = \frac{M^z_{11} Z_\infty + M^z_{12}}{M^z_{21} Z_\infty + M^z_{22}} \tag{13}$$

and the phasis of input impedance can be expressed as : $\Omega_i = \arctan[\Im(Z_i), \Re(Z_i)]$

Determination of porosity in first centimeters of sample be possible by comparing measured and modelised phasis. The main principle is to minimize the following function :

$$\Theta = (\Omega_m - \Omega_i)^2 \tag{14}$$

Finally, by doing the same operation for each pixel, it is possible to have a 3D representation of density variation for first centimeters (fig. 7). For example it is shown that even if at the surface of the sample, infrared images show some defect (fig. 3) porosity is pretty good under the sapwood (fig. 6).

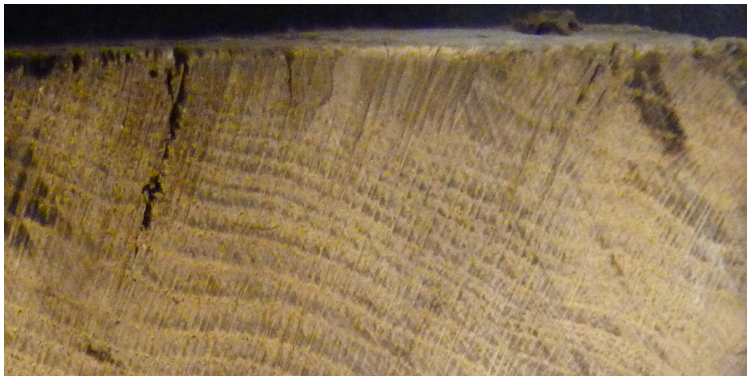

Fig. 6. Cross section of the sample of wood

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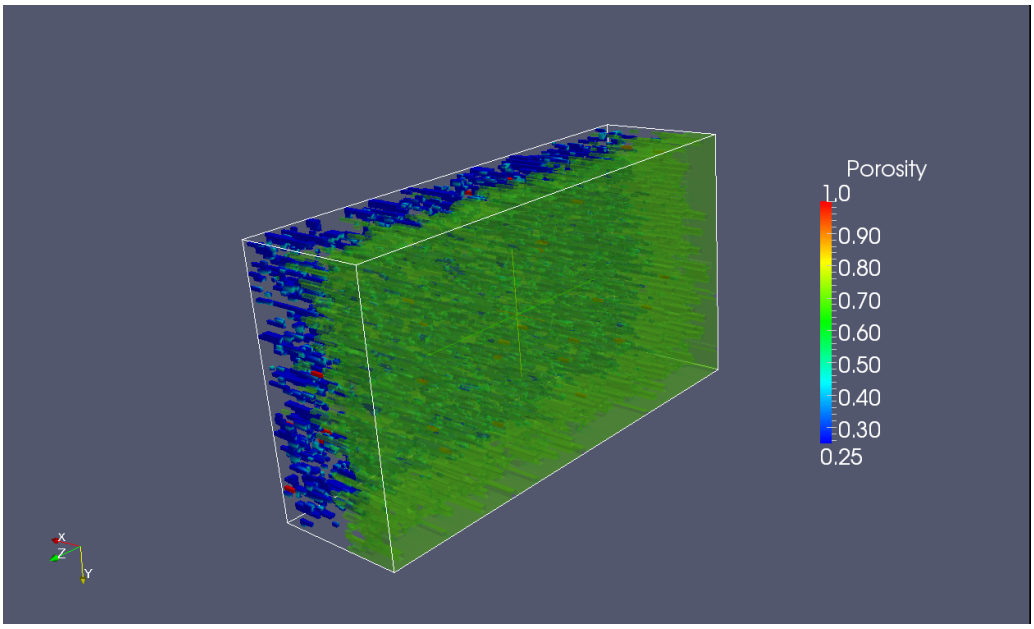

Fig. 7. 3D representation of density variation for a set of 100x160 pixels images

3. Results and discussion

Measurements are first compared with 10,000 thermal models. Results shows that for most of pixels, a 1D analysis can be used and a simple description can be entered, like logarithmic evolution of porosity in first millimeters of sample, without a detailed knowledge of its microstructure. The use of model comparison instead of numerical inversion to identify thermophysical properties is very fast (6000 IR images of 100x160pixels and 10,000 models processed in less than 10 minutes with a python 2.7 code developed in our laboratory).

Models with crack representation work fine with low variation of porostiy around the crack. However, complex structures (random distribution of spherical pores with cracks e.g) need a better description of thermal behaviour and the purpose of current works is to develop more models based on various definition of porosity evolution. Anisotropic effects due to fibers orientation seems to be not visible but a targeted analysis must be carried out to evaluate potential disturbances. Evolution of frequencies of SWEEP signal may also reconsidered and various SWEEP signal need to be studied to give limits to method efficiency i.e to know the maximal depth of possible investigation, to have a better description of frequential response,...

Due to the correlation between water content and thermal effusivity in porous media [10], moisture detection may be considered for further investigations.

At this time, density variation is determined but thermal methods used in this work could be associated with mechanical methods to obtain an absolute density value.

4. Conclusion

Beginning with a first range of thermal behaviours (10,000 models), feasibility study shows that it is possible to characterize density variations in most of cases. With additional models (i.e other than fractal description of porosity and random models), the method could be refined to make it more reliable. It is desirable to use the method in association with another NDT or SDT methods to clearly identify absolute value of density in the structure.

5. Acknowledgement

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