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Experimental ultrasonic characterization of polyester-based materials for cultural heritage applications

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ABSTRACT

For several years, the Réunion des musées nationaux – Grand-Palais has produced polyester resin reproductions in order to replace marble sculptures that have weakened by outdoor exposure. These objects are made of a complex multilayered polyester composite material including reinforcements to ensure the mechanical strength of the final structure and mineral fillers that allow to imitate the original aesthetics. However, the final structure also weakens because of constant outdoor exposure and ageing. This observation leads today to conduct research related to the structural health monitoring of reproductions for preventive conservation of cultural heritage. This paper presents a nondestructive technique to study the properties of the composite material used to produce reproductions of marble sculptures. Firstly, classical ultrasonic contact measurements were performed to estimate bulk properties and Rayleigh wave velocity. Secondly, experimental Rayleigh wave was measured using contact and laser vibrometry methods. The results show the potential of using ultrasonic surface wave propagation and laser vibrometry method to develop a minimum contact technique to study these polyester-based materials. The maximum relative uncertainty with respect to the expected theoretical Rayleigh wave velocity was close to 12%.

1. Introduction

In cultural heritage, the manufacturing process of reproductions is handmade and it consists of various polyester/reinforcements/fillers arranged leading to a composite structure that imitates original artwork [1]. The manufacturing of polyester-based composites is similar to that used in design of marine structures [2,3]. The manufacturing process of these reproductions could be advantageously optimized by using proper measurement techniques that allow estimating the characteristics of the materials.

Ultrasonic techniques are usually carried out in non-destructive testing and evaluation of materials because they can be used both in laboratory and *in situ* conditions to characterize and determine physical and mechanical properties of materials [4]. Fields of applications are very wide: forestry [5–7], microelectronics [8,9], crack detection [10,11], polymer/composites industry [12,13], and cultural heritage [14–16].

These properties can give several informations of the material state and they can be deduced from the measurement of different ultrasonic wave velocities of a sample. Indeed, the ageing of the sample can cause a variation of the wave velocity due to appearance of cracks or elastic behavior modifications. In order to operate with a minimum contact on the structure, it is advantageous to measure the waves propagating at the surface using an optical detection technique. In one hand, surface waves velocity depends on material properties such as density, elastic constants, and, furthermore, porosity, structure and manufacturing process. On the other hand, scanning laser vibrometry is a well-known technique used in the montoring of guided wave propagation in composite materials [17,18]. Therefore, surface wave propagation, laser vibrometry and signal processing techniques could thus be convenient for qualitative and quantitative characterization of the polyester-based materials.

Recent ultrasonic studies have been done on original marble artworks [19–21]. However, no studies have been conducted for the ultrasonic nondestructive characterization of composite materials used for reproductions of marble sculptures. Thus, the aim of this research is more precisely to use classical ultrasonic testing

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applied to the measurement of mechanical properties (apparent Young's and Shear Moduli, Poisson's coefficient) and Rayleigh wave propagation. For this study, polyester-based composites were tested using ultrasonic contact transducers in order to generate the compression, the shear and Rayleigh waves successively. Firstly, acoustical bulk wave velocities were measured to estimate mechanical properties and theoretical Rayleigh wave velocity. Secondly, experimental Rayleigh wave was measured using a contact method and using laser vibrometry for its detection and monitoring along the propagation path. In order to study surface wave propagation, three calculations of Rayleigh wave velocity are thus established using: theoretical equation [22], contact measurement [23] and spatio-temporal and two-dimensional FFT method representations [24]. The results show the potential of surface wave propagation and laser vibrometry method to discriminate the different samples.

2. Materials and methods

2.1. Experimental protocol

The experiments were performed on 5 parallelepipedic composite samples and based on the classical ultrasonic testing of homogeneous isotropic materials. A 1 MHz broadband ultrasonic contact transducer (compression or shear, Ø = 13 mm, Panametrics) was used as a transmitter. The pulser used in the experiments is the JSR Ultrasonics DPR300 and the excitation signal was a short electrical pulse.

For each material, acoustical bulk wave velocities were measured in transmission mode in the three axes of samples in order to estimate mechanical properties and Rayleigh wave velocity. A first experimental value of Rayleigh wave velocity was measured using a contact transducer as a receiver. Finally, a OFV-505 Polytec vibrometer was used to detect and monitor Rayleigh wave in order to estimate a second experimental value of its velocity. All received ultrasonic signals were recorded by a LeCroy WaveSurfer 24Xs digital oscilloscope at a sampling frequency of 100 MHz and acquired over 1000 sweeps average in order to obtain high signal-to-noise-ratio signals.

2.2. Materials and acoustical/mechanical assumptions

The manufacturing of a reproduction consists of the successive addition of different layers of materials. The gelcoat is the external layer that imitates the effect of marble, made of a resin combined with marble powder (MP). Fig. 1 shows a typical example of gelcoat. It will be assumed to be an isotropic material due to the isotropic origin of matrix and the random orientation of grains [25]. In fact, during the manufacturing process, gelcoat is prepared as a mixture of resin and marble grains until a homogeneous viscosity is obtained. Before solidification, this last permits the molder to use gelcoat as some kind of glue that can be distributed over the artwork mold using a paintbrush (the same principle used in marine structures).

Stratification resin layers are then added as reinforcement of the final multilayered structure. These layers are made of a polyester resin that is reinforced by glass mat. The mat is composed of cut fibers randomly distributed in the plane that results in quasi-isotropic in-plane macroscopic behavior [2]. Each polyester/glass mat layer is therefore characterized by only three effective independent elastic constants.

A light resin is added in order to fill the body of the reproduction until its weight is equivalent to the weight of the original statue. Light resin is a mixture of polyester resin and glass microspheres. A glass microsphere replaces locally a volume occupied by polyester by an equivalent volume with less density. The concentration of microspheres in the polyester matrix is assumed to be uniform throughout the composite. Thus on a macroscopic scale, the light resin may be regarded as quasi-homogeneous and quasi-isotropic material [26].

Finally, the resulting structure (reinforced composite) will be assumed as a transversely isotropic material since is a multilayered material in the thickness axis resulting symmetric with respect to a rotation about an axis parallel to thickness. The study was thus realized on parallelepipedic composite samples assumed to be homogeneous and weakly dispersive (4 isotropic and 1 transverse isotropic). The dimensions of the samples are 210 × 120 × 27 mm (directions $\vec{x_1}, \vec{x_2}, \vec{x_3}$) and their description is given in Table 1. For our experiments, the reinforced composite sample is composed of a gelcoat layer that represents about 50% of the thickness of the composite.

2.3. Elastic properties measurement and Rayleigh wave velocity estimation

Let us note that a solid is isotropic if its properties are independent of the wave propagation direction. Isotropic solids can be characterized by two kinds of waves that propagate within: compression and shear waves [22]. Assuming that the medium is weakly dispersive, the phase delay and the group delay are superimposed. Wave velocities were computed using the distance between transducers and the time-of-flight (TOF) of transmitted ultrasonic pulse (Eq. 1):

$$v_{P,S} = \frac{d}{TOF} \tag{1}$$

where d is the length ($\vec{x_1}$), the width ($\vec{x_2}$) or the thickness ($\vec{x_3}$) according to propagation direction; P stands for compressional wave and S stands for shear wave. In order to estimate experimental group velocities, determination of TOF can be done using the max-envelope method (obtained from the Hilbert transform, [27]).

For an isotropic material, $v_{P,S}$ is the same for all directions and therefore, $v_{P,S}$ is assumed to be the average of the experimental velocities measured in the three propagation directions. In the case of the transverse isotropic material, $v_{P,S}$ is assumed to be the average of the experimental velocities measured through the width and the length (i.e. $\vec{x_1}$ and $\vec{x_2}$). Density was calculated for each sample from the bulk weight and volume sizing. For isotropic materials mechanical properties can be estimated from ultrasonic wave velocities as follows Eqs. (2)–(4), [4]):

$$E = \rho v_S^2 \frac{3v_P^2 - 4v_S^2}{v_P^2 - v_S^2} \tag{2}$$

$$G = \rho v_S^2 \tag{3}$$

$$\nu = \frac{\left(\frac{v_P}{v_S}\right)^2 - 2}{2\left(\left(\frac{v_P}{v_S}\right)^2 - 1\right)} \tag{4}$$

where E is the Young's Modulus, G the Shear Modulus, ν the Poisson ratio and ρ the density. For a transverse isotropic material, these calculations are valid for the mechanical properties limited to the transverse direction (where the composite is assumed to be isotropic).

It is also possible to estimate the theoretical Rayleigh wave velocity using Viktorov's formula ([22], Eq. (5)):