

# Simulation of an Ultrasonic Immersion Test for the Characterization of Anisotropic Materials

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## Abstract:

We develop a numerical model for simulating ultrasonic immersion tests aimed at the mechanical characterization of anisotropic materials. In particular, the analysis is focused on a fiber reinforced composite. The numerical simulation gives results very close to those obtained in certain experiments: this enables the use of the numerical model for developing and optimizing the experimental set-up, and for extending the experimental procedure to materials with more complex anisotropic behavior.

**Keywords:** Mechanical Characterization, Fiber Reinforced Composites, Anisotropy, Immersion Ultrasonic Test, Wave Propagation.

## 1. Introduction

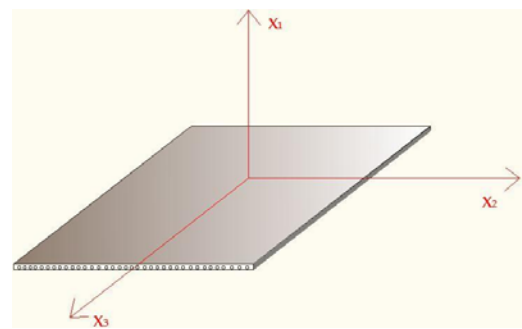
Ultrasonic testing may be a powerful, fast and effective method for nondestructive characterization of the mechanical properties of traditional and new materials. This innovative promising application field requires the analysis of suitable models, which describe the physical and mechanical phenomena involved in the experiments.

Especially in presence of complex mechanical behaviors (anisotropy, finite deformations, damage, etc.), several difficulties may arise in the study of the related elastodynamic problems. For example, in the case of anisotropic materials the propagation of ultrasonic waves is strongly related to their directions with respect to the directions of symmetry of the material response. In this context, numerical simulations may be very helpful for designing and developing experimental set-ups and for a deeper understanding of the results of experiments. Here, using COMSOL, we construct an innovative numerical model for simulating an immersion ultrasonic test for the mechanical characterization of anisotropic materials. The model, which is full 3D, consider the coexistence of a fluid and a solid phase. The analysis is specialized to the case of fiber-reinforced composite materials with a single layer of carbon

fibers (CFRP). The numerical model is validated by some experimental results obtained in some tests performed at Politecnico di Bari.

## 2. Theoretical Model: Wave propagation in anisotropic elastic materials

In this paper we study the propagation of ultrasonic waves in fiber-reinforced composite materials with a single layer of carbon fibers (CFRP). This material may be modeled as linearly elastic transversely isotropic, with an axis of transverse isotropy coincident with the axis of the fibers (Figure 1).



**Figure 1.** Fiber-reinforced composite material with a single layer of carbon fibers

Under the current hypothesis, the elasticity tensor has the following form

$$\mathbb{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (2.1)$$

with  $C_{12} = C_{11} - 2C_{66}$ ; thus the mechanical response may be described by assigning five independent elastic constants.

The propagation of elastic waves in absence of body forces is described by the equation of motion

$$\operatorname{div} (\mathbb{C} [\nabla \mathbf{u}]) = \rho \ddot{\mathbf{u}} \quad (2.2)$$

where  $\rho$  is the mass density,  $\mathbf{u}(\mathbf{x}, t)$  is a planar elastic wave propagating in direction  $\mathbf{n}$  and  $\mathbb{C}$  is the elastic tensor.

The condition for wave propagation is usually written in the form

$$[\Gamma - \rho v^2 \mathbf{I}] \mathbf{a} = \mathbf{0} \quad (2.3)$$

(Fresnel – Hadamard’s condition or Christoffel’s equation). In (2.3),  $v$  is the phase velocity,  $\mathbf{a}$  is the direction of wave motion (its amplitude is  $|\mathbf{a}|$ ) and the second order tensor  $\Gamma$ , called the Christoffel’s tensor, is given by

$$\Gamma(\mathbf{n}) = \mathbb{C}^t [\mathbf{n} \otimes \mathbf{n}] \quad (2.4)$$

where the superscript “t” represent the operation of minor transposition for fourth order tensors. The Christoffel’s tensor  $\Gamma$ , which is related by (2.4) to the elastic tensor  $\mathbb{C}$ , to the mass density  $\rho$  and to the direction of propagation  $\mathbf{n}$ , plays a crucial role in the study of the propagation of elastic waves.

In particular, the Fresnel – Hadamard’s condition (2.3) links the elastic constants (i.e., the components of  $\mathbb{C}$ ) to the properties of the propagating elastic waves. Thus, by employing the Fresnel – Hadamard’s condition, it is possible to experimentally determine the elastic constants by measuring a set of bulk phase velocities of ultrasonic waves propagating in the material along suitable directions (inverse problem).

### 3. Experimental Results

We determine the elastic constants of a fiber-reinforced composite specimen (SIKA CARBODUR S 1012 EP251 – CR 508 – 30) by an ultrasonic immersion tests. To do this, we use an innovative experimental device, specifically designed and built at Laboratorio Ufficiale Prove Materiali “M. Salvati” (Politecnico di Bari) for the ultrasonic mechanical characterization of anisotropic materials (Figure 2). The main features of this device are a goniometer tool and

an advanced data acquisition system. The goniometer allows to rotate the sample during the test, enabling to measure the time-of-flight of ultrasonic waves through the sample for different angles of propagation.



Figure 2. Immersion ultrasonic set-up

In order to estimate all the five elastic constants of the material, we consider two different modes of propagation for the ultrasonic waves.

In the first mode of propagation we put the specimen with the fibers ( $x_3$  direction) parallel to the axis of rotation of the goniometer; in this case, the ultrasonic waves propagate in the isotropic plane  $\pi_{12}$  (Figure 3);

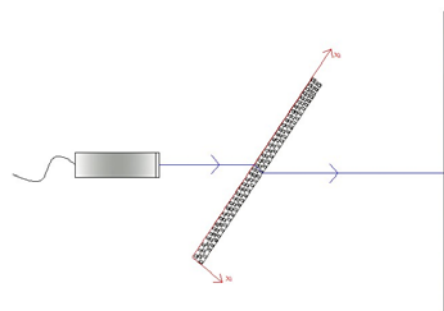


Figure 3. Wave propagation in isotropic plane  $\pi_{12}$

The second mode of propagation is obtained by repositioning the sample into the device, with the axis of rotation of the sample coincident with the axis  $x_2$  (Figure 4); in this case the propagation takes place in the plane containing the fibers  $\pi_{13}$ , i.e. in the anisotropic plane.

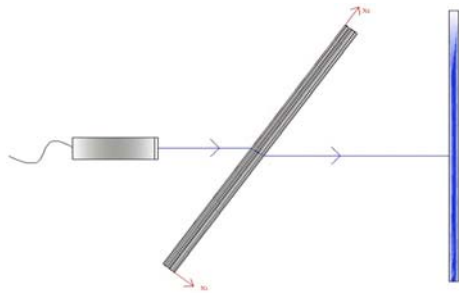


Figure 4. Wave propagation in anisotropic plane  $\pi_{13}$

The measurement of the velocities of transverse and longitudinal waves in suitable directions, together with the measurement of the mass density  $\rho$ , enable us to determine the following five elastic constants of the CFRP; in short, the calculations are basically based on the analysis of the propagation condition (2.3).

$$C = \begin{bmatrix} 15,48 & 8,72 & 6,37 & 0 & 0 & 0 \\ 8,72 & 15,48 & 6,37 & 0 & 0 & 0 \\ 6,37 & 6,37 & 181 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4,098 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4,098 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3,38 \end{bmatrix} \text{ GPa.} \quad (3.1)$$

#### 4. Use of COMSOL Multiphysics

Numerical simulations are a powerful tool for a deeper understanding of the phenomena involved in the experiments and for design more efficient experimental setup.

In the present case, we simulate the propagation of ultrasonic waves in an immersion test on a fiber reinforced composite sample using the GENERAL FORM PDE module of COMSOL. Indeed, this module may solve many classical PDE, including some wave equations. Moreover, there are other two relevant motivations for this choice: 1) it is possible to model both the fluid (water) and the solid (fiber-reinforced composite) domain; 2) it is easily possible change the predefined forms of the PDE for

adapting them to the elastodynamic mechanical model (2.1-2.4).

For the analysis in the time domain we use the time dependent solver: this approach is suitable for problems like elastic waves propagation.

The model here showed is full 3D and follows simplified 2D models developed before. Here, the domain “solid”, which represents the sample, is surrounded by the domain “water”; inside the latter, we have built an interface element that simulates the immersion ultrasonic transducer (see Figure 5).

The material parameters for the “solid” domain come from the above described ultrasonic immersion tests on a sample of CFRP. In particular, we consider the values (3.1) of the five independent elastic constants and a mass density of  $1556 \text{ kg/m}^3$ .

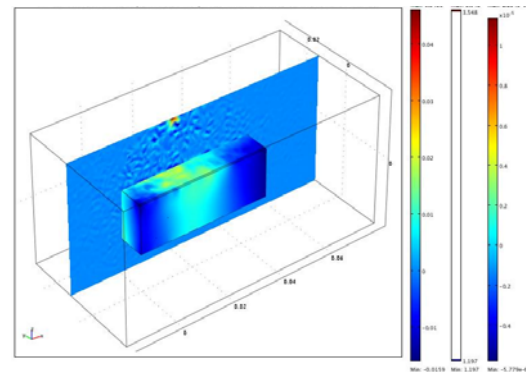


Figure 5. Overview of the geometry of the model

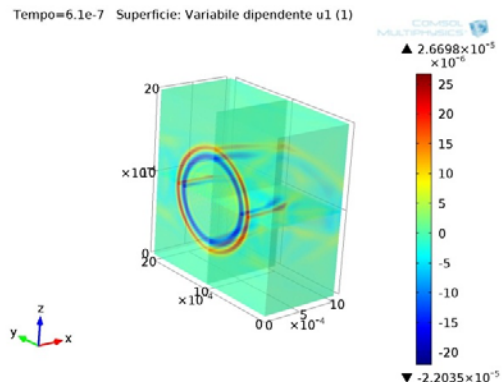
#### 5. Numerical results

Given the elastic constants, the analysis is focused on the determination of the speed of ultrasonic longitudinal and transversal waves through the evaluation of their time of flight across the fiber-reinforced composite specimen (forward problem).

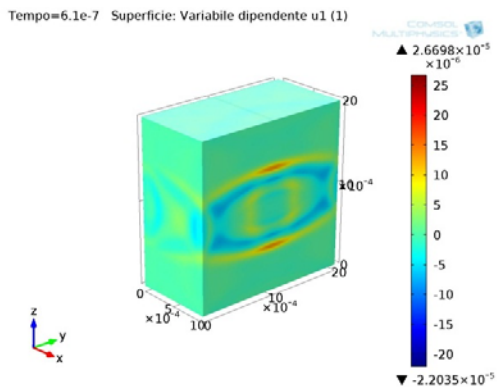
In particular, we employed two numerical models, simulating the two modes of propagation in the ultrasonic immersion test described in Section. 3.

In the first numerical model (see Figures 6-9) the wave propagation takes place in the isotropic plane  $\pi_{12}$ . We first simulate the wave propagation in the direction orthogonal to the surface of sample, for determining the speed of longitudinal waves. Then, we simulate the propagation with an angle of incidence of the

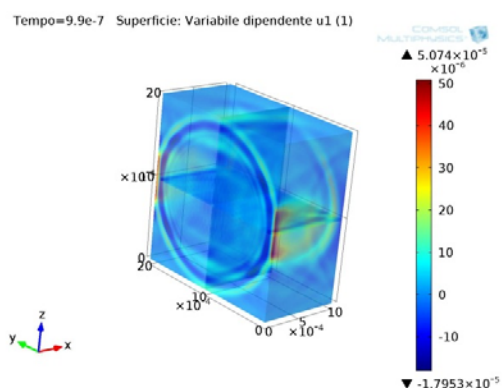
wave beam greater than the first critical angle, for determining the speed of transverse waves.



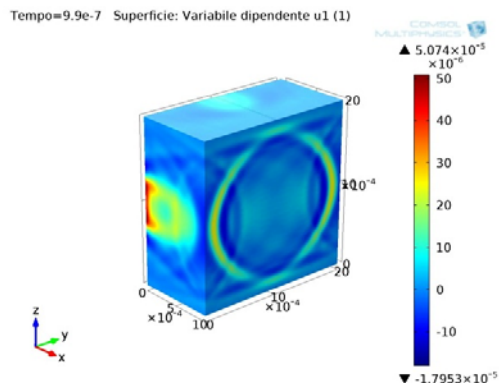
**Figure 6.** Wave propagation in the isotropic plane  $\pi_{12}$  ( $t = 6,1 \cdot 10^{-7}$ s); front view



**Figure 7.** Wave propagation in the isotropic plane  $\pi_{12}$  ( $t = 6,1 \cdot 10^{-7}$ s); rear view



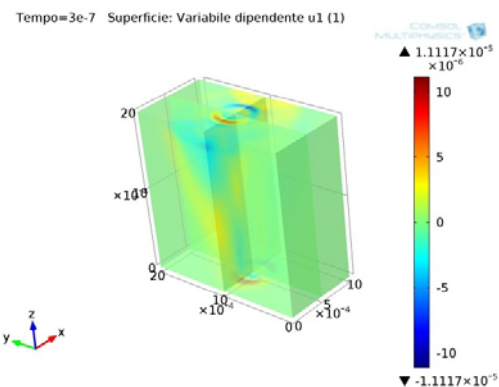
**Figure 8.** Wave propagation in the isotropic plane  $\pi_{12}$  ( $t = 9,9 \cdot 10^{-7}$ s); front view



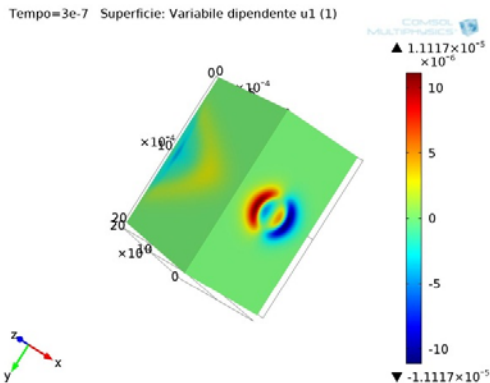
**Figure 9.** Wave propagation in the isotropic plane  $\pi_{12}$  ( $t = 9,9 \cdot 10^{-7}$ s); rear view

In this way, we determined a longitudinal waves speed  $v_L = 3100$  m/s and a transversal waves speed  $v_T = 1420$  m/s: this values are very close to the speed experimentally evaluated.

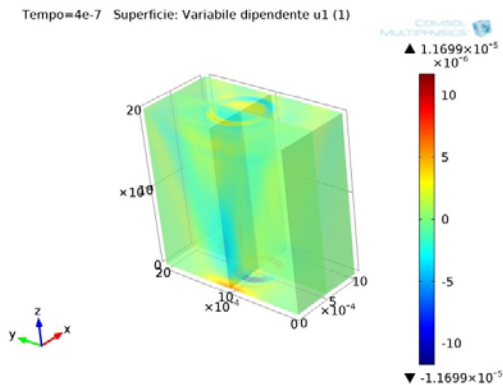
In the second model the propagation of the ultrasound beam occurs in the plane containing the fibers, i.e. in an anisotropic plane  $\pi_{13}$  (Figure 10-13). Also in this case we simulate the propagation of longitudinal waves by arranging the ultrasonic beam perpendicularly to the surface of the specimen, and the propagation of transverse waves by tilt the ultrasonic beam more than the first critical angle with respect to the surface of the specimen. The calculated longitudinal and transverse are  $v_L = 3450$  m/s and  $v_T = 1436$  m/s, respectively: this values are similar to those experimentally evaluated as well.



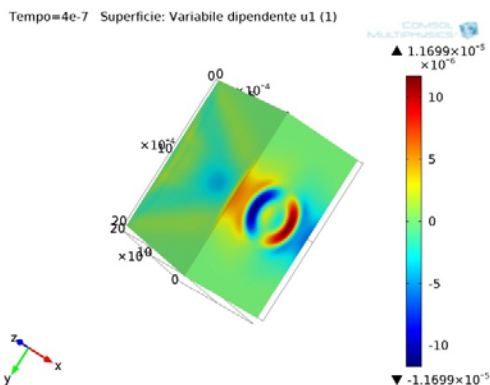
**Figure 10.** Wave propagation in the anisotropic plane  $\pi_{13}$  ( $t = 3,0 \cdot 10^{-7}$ s); front view



**Figure 11.** Wave propagation in the anisotropic plane  $\pi_{13}$  ( $t = 3,0 \cdot 10^{-7}$ s); rear view



**Figure 12.** Wave propagation in the anisotropic plane  $\pi_{13}$  ( $t = 4,0 \cdot 10^{-7}$ s); front view



**Figure 13.** Wave propagation in the anisotropic plane  $\pi_{13}$  ( $t = 4,0 \cdot 10^{-7}$ s); rear view

Besides the evaluation of the wave speeds, the numerical model allows for: 1) the identification of the areas of maximum intensity of the emerging ultrasound beam, and the measurement

of the phase velocity and the phase angles: this is worthwhile for defining the optimal positions of the transducers in the experiments; 2) the determination of the optimal angles of incidence of the ultrasound beam on the surface of the sample for getting the maximum energy for the longitudinal and transverse waves inside the sample; 3) the analysis of the effects of rotations of the specimen and/or of the transducers on the propagation of the ultrasonic waves, for improving the handling of the specimen in the tests; 4) the determination of the planes of symmetry of the mechanical response.

## 6. Conclusions

The proposed numerical model is innovative in the field of ultrasonic NDT since it is full 3D model and since it considers the coexistence of two phases (the fluid and the solid). The numerical results here obtained are very close to those obtained experimentally: this validate the capability of the model for prediction and interpretation of experimental data. From this starting point may stem a number of future applications like, for example, the mechanical characterization of materials with more complex anisotropic behavior, and the analysis of ultrasound propagation in anisotropic materials with defects, damages, and initial stress (residual and/or applied).

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