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Fuzzy logic response to Young's modulus characterization of a flax–epoxy natural fiber composite

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ABSTRACT

Most design approaches use the experimental elastic modulus as input variable to describe the material properties. In most cases the uncertainty and the variability of the modulus are neglected. In the worst case this can lead to bad estimations of the material performance and more iterations to the final solution. The purpose of this work is to reconcile the Young's modulus of three configurations ($[0]_{10}$, $[0]_{20}$ and $[\pm 45]_{10}$) of flax–epoxy composites obtained by different techniques including acoustic impulse, tensile and bending tests, according to ISO and ASTM standards. Results obtained with these techniques all show different levels of variability in Young's modulus values. A fuzzy logic model is used to obtain a simplified view of linguistic variables representing the modulus of elasticity and to reconcile different modules by including the uncertainty inherent to the different measuring techniques. Results have shown a strong potential for fuzzy logic to reconcile the disparity of Young modulus of natural fiber composites.

1. Introduction

In addition to be considered eco-friendly materials, natural fiber composites (NFCs) have interesting mechanical properties and compete with non-degradable materials in several fields of application [1,2]. Indeed they present low density, good mechanical properties, low cost, and ease of machining [3]. However the disparity of their properties, which results in variability of their behavior, prevents the growth of their use, unlike synthetic fiber composites. Many authors [4–7] have demonstrated that the NFC, specifically the flax–epoxy composite has a large dispersion in its mechanical properties. Therefore, repeated measurements in equal conditions using different samples will give a variation in measurement results. For the same flax–epoxy material, there is also a noticeable difference between tensile and flexural modulus. Table 1 shows the compiled results of tensile modulus for unidirectional (UD) and weave varieties of flax–epoxy composites. Though this list is not exhaustive, it provides a snapshot of the variability of estimated values of tensile modulus. It can be observed that the tensile modulus depends on fiber volume fraction and the nature of epoxy used in the matrix, the process used and the fabric type of fibers. For woven fabrics the amount of waviness in the yarns may also affects tensile modulus [8]. To assess their sustainability and promote the use of these materials in the industry, their mechanical behavior must be carefully studied [9].

Lord and Morrell [10] conducted a study to identify the sources of uncertainty in the calculation of the tensile modulus. They demonstrated that the accuracy in modulus determination is strongly affected by the quality of the data acquired, the test set-up and the material availability. From these three parameters alone it is reported that the uncertainly can vary from 1% to 6%. Baley [6] observed a large spread of Young modulus's of flax fiber. The uncertainly of Young's modulus of flax fiber can reach up to 28% [5] while the uncertainly of glass fiber is around to 3% [11]. This dispersion is explained by many different parameters that influence the quality of fibers, in particular the varying morphology of individual natural fibers. This heterogeneity depends of the climate [12], maturity at harvest time [13], surface treatment [14,15], processing parameters, and the presence of variable proportions of porosity [16] in the material. In addition, variations in the amount of waviness in the yarns can affect the mechanical properties of woven fabric composites. On the other hand, the manufacturing method of flax–epoxy also has a great influence on the tensile properties of the composites. In particular the manufacturing process influences the flax fiber length and the length distribution [17].

The importance of elastic properties of materials for design and engineering applications is such that there are a large number of experimental techniques that have been developed to estimate them. These techniques can be classified into two groups: destructive and non-destructive methods. Destructive methods include tensile, compressive and flexural tests, etc. These methods measure directly the strain and the stress during the test. The elastic tensile modulus of fiber- reinforced plastic composite is typically measured in the strain range of 0.05 to 0.25% and 0.1 to 0.3% for ISO 527-4 and ASTM D3039 standard norms respectively. Shah et al. [18] have showed that although the apparent stiffness is fairly constant in this strain range (0.05 to 0.25%) for unidirectional E-glass–polyester composites, there is significant variation in the

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Table 1
Tensile modulus of different models of flax fibers from the literature.

Fabric type	Fiber fraction V_f (W_f)%	Epoxy type	Process	E_T (GPa)	E_F (GPa)	Reference
Weave Warp knit $[0/90]_2$	28	Araldite MY-750	Hand lay-up	14	15	[9]
UD	59 to 64	Epikote 828LVEL	Hand lay-up	32.1 ± 0.4	23	[10,11]
Weave Warp knit $[0/90]_2$	28	Araldite MY-750	RTM	14	17	[9]
Weave	54	Resin SP106	RTM	1.8	7	[12]
Weave Twill 2 × 2	31 to 36	Huntsman LY5150	Autoclave	9.1 ± 0.3 to 10 ± 0.2	5.2 to 9.2	[13–16]
UD $[0]_7$	40	HM 533	Autoclave	26 ± 1	18 ± 3	[17]
Weave $[0]_3$	(35.5)	Ampreg20	Resin infusion	6.86 ± 0.14–		[18]
Weave [0/90/0]	(35.1)	Ampreg20	Resin infusion	7.37 ± 0.15	–	[23]
UD	38	–	–	15.97 ± 1.37	–	[15]
UD	57	Epikote 828LVEL	Thermo-compress	26.3 ± 2.1	18	[10,11]

E_T = tensile Young modulus; E_F = flexural Young modulus; W_f = weight fraction V_f = volume fraction.

apparent stiffness for flax-polyester due to their nonlinear stress–strain curve. This nonlinearity has reduced the Young's modulus by 30% for this NFC. Beats et al. [19] have also observed major influence of the strain range on the variation of Young's modulus of flax–epoxy. Actually, there is not standard norms which define the exact strain range for the determination of tensile modulus value of NFCs. For ISO standard 527-4, several authors use two approaches (0.05 to 0.25% or 0.05 to 0.1% strain range) to measure the tensile modulus and obtain different values of tensile modulus.

Nondestructive methods include ultrasonic measurement (pulse-echo or through transmission) and impulse excitation technique (or resonance method) [20,21]. These techniques are based on knowing the dimensions and densities of the samples, and are therefore often called indirect methods. The resonance method measures the resonant frequencies of materials in vibrational modes. The elastic proprieties of the specimen are related to its mechanical resonance frequency. The pulse method measures the time for the ultrasonic pulse to travel through the specimen from the transducer. It is possible to calculate Young's and shear moduli of the material by the knowledge of the travel time for longitudinal and transversal ultrasonic waves. The advantage of nondestructive techniques compared to destructives ones is that they can measure a wide variety of specimen shapes and sizes. They are also characterized by a good measurement precision over a wide temperature range. The specimen is also easy to prepare. But this technique is very sensitive dimensional variations and the mass of the test specimen [20] and to the anisotropy of the material [22]. It is one of the major disadvantages for their application for determination of elastic constants of NFC.

Whether destructive or nondestructive, most techniques use several parameters that are often measured with uncertainty. Furthermore, these parameters differ depending on the various tools and/or standards used. It is agreed that the quality of assessment is limited due to sources of uncertainties arising at several levels and caused by the testing method, the influence of the environment, human factor, etc.

Current design approaches use determinist elastic proprieties variables as inputs to describe the mechanical properties of the material. In the worst cases, neglecting the uncertainly and variability can lead to a bad estimation of the performance or the damage of the material [23]. Despite this influence most of the reliability analyses techniques do not take into account the uncertainties and variability of these input variables. For NFC materials and flax–epoxy particularly, the inherently large dispersion of their mechanical proprieties (due to the variable quality of natural fibers and the variable experimental errors obtained from different characterization tools or techniques) can certainly lead to bad estimations of the performance and more iterations to the final solution. Most of the techniques cannot be compared or reconciled directly because they are measured in different units, but the precision and the repeatability of one method can be lead to have a confidence to one method that another. Therefore, using mean or median values to correlate or to reconcile the values obtained by different methods or standard norms can lead to bad estimations. For this, it will be important to develop new design approaches which consider the variability of the mechanical properties of NFCs and the uncertainly of the characterization process. Fuzzy logic (FL) stands among the new interesting approaches that incorporate all the variabilities and uncertainties in the analysis phase. This technique enables potential reconciliation of the tensile modulus values obtained by different techniques and standard norm.

The FL technique is a soft modeling tool which has been used for linear and nonlinear systems. Fuzzy logic theory was developed by

Table 2
Characteristics of «FlaxPreg BL 150».

Fiber fraction	By weight W_f	50%
Fiber fraction	By weight W_f By volume V_f	50% 45%
Weave pattern (warp to weft ratio)	1/1	
Fiber density ρ_f (g/cm^3)	1.45	
Weight of flax M_S (g/m^2)	150 g of weave/m^2	
Theoretical density of tissue ρ_c (g/cm^3)	1.31	

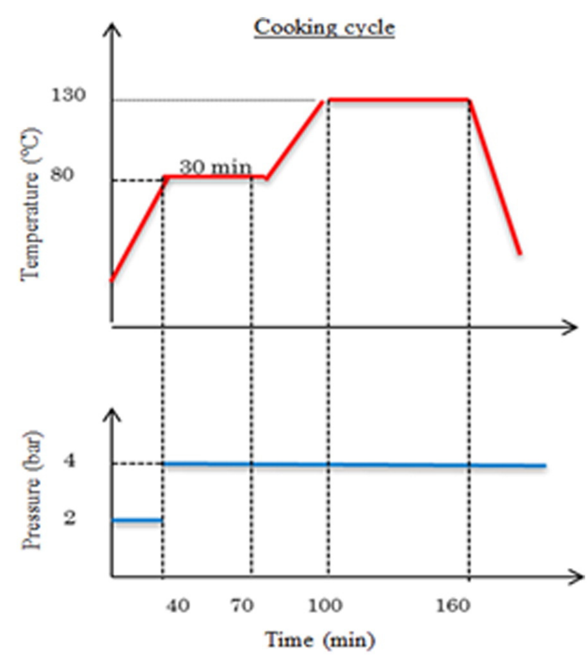

Fig. 1. Processing cycle applied during plate manufacturing.