

Genetic algorithm-based optimization of advanced materials

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The purpose of this paper is to exploit genetic algorithms for the optimization of several characteristics of the woven composite materials as function of the nature of the polymer chosen as matrix, of the nature of fibres, and of the fabric geometrical parameters. Simulation results and comparative analyses with experimental data are presented.

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1. Introduction

Textile structural composites represent a class of advanced materials which are reinforced by textile perform for primary structural applications. Making use of the unique combination of light weight, flexibility, strength and toughness, textile structures have been recognized as an attractive reinforcement form for many applications. The complexity of textile composite materials is due to the fact that there are many factors which influence the characteristics of the composite, such as: the nature of the matrix and the properties of the fibers, the nature and geometry of the fibers and fabric. Due to this complexity, which affects both the mechanical behavior and the elastical properties of this type of material, research has been devoted to optimization possibilities for the material as a whole, as well as to developing new models to better approximate their structure, configuration and real behavior, [1-3].

Modern stochastic optimization techniques involving evolutionary computation such as genetic algorithms have been shown to be efficient tools to find solutions close to the global optimum, [4]. The paper presents in Section 2 the genetic algorithm implementation, while, in Section 3, the main characteristics of the woven composite materials are discussed. The optimization process results and comparisons with experimental data are commented in Section 4. Some conclusions and future research directions are presented in the final section.

2. GA engine implementation

Genetic algorithms attempt to simulate Darwin's theory of natural selection and Mendel's work in genetics on inheritance: the stronger individuals are likely to survive in a competing environment. In a similar way, the genetic algorithm evaluates many solutions of an assigned

problem and, combining them, the best one can be found. A very important property of genetic based search methods is that they maintain a population of potential solutions, while all other methods process a single point of the search space. They are also derivative free optimization methods, as they do not need functional derivative information to search for a set of parameters that minimizes (maximizes) a given objective function. Using such algorithms one can obtain robustness and flexibility, [4].

The genetic algorithm considers the solution of the optimization problem as an individual. The characteristics of an individual are due to the genes of his chromosomes in much the same way the characteristics of a possible solution are due to its parameters. One can use further the analogy: as a desired individual can be created through an evolutionary process starting from a random choice of individuals forming a population, the optimal solution can be found through an adequate combination of random sets of solutions. The stopping criterion can be: evolution over a prescribed number of generations, the goodness of best solution or any problem specific condition. In order to implement the genetic algorithm we have adopted a philosophy inspired by GALib, a C++ library for genetic algorithms objects, [5].

The basic steps of the algorithm can be described as follow:

- *initialize population*
- *repeat*
- *select individuals for mating*
- *mate individuals to produce offsprings*
- *mutate offsprings*
- *insert offsprings into population until stopping criteria*

For our application, each chromosome had three genes, encoding different fabric parameters (selected, for example, among: uw, h, uf, gw). We have used a decimal

format for chromosomes, exploiting an implementation of the traditional method for converting binary strings to decimal values, [5] and, for the beginning, the standard simple genetic algorithm, described by Goldberg, [4]. This algorithm uses non-overlapping populations and optional elitism. For each generation, an entirely new population is created by selecting individuals for mating from the previous population, according to a specified selection method. The stopping criterion is given by the condition that the ratio between the maximum and the minimum values of the individual fitnesses exceeds a specified value, in our case 0.98. After a large number of tests, the most efficient crossover operator proved to be the three-point one, while the most effective selection scheme proved to be the Stochastic Remainder Sampling Selection, [4].

Having in view advanced implementation platforms with CPUs operating at GHz, the proposed approach is able to provide competitive or nearly optimal solutions in a practical computing time. We have extensively tested the genetic algorithm in order to prove its adequacy for this application.

3. Woven composite materials

2.1 Textile preforms

The term “textile structural composite” is used to identify a class of advanced composites utilizing fiber preforms produced by textile forming techniques, for structural applications. Textile composites are being considered for primary structural applications where out-of-plane properties are also important so that the structure can take up the secondary loads due to load eccentricities, local buckling, etc. Use of textile preforms is one of the most important developments in the fiber-reinforcement polymer composite sector for structural applications. The major textile forming techniques for composites reinforcement are weaving, knitting, braiding, and *nonweaving*. In general, textile composites offer better dimensional stability over a large range of temperatures, better out-of-plane properties, better impact resistance, subtle conformability, and deep draw moldability / shapability [1,3,6,7]. Fibers in textile form present a good out-of-plane properties, and good fatigue and impact resistance. Additionally, they have better dimensional stability and conformability.. In particular they offer greater flexibility in processing options, with associated economies. With regard to mechanical analysis, the presence of the crimp regions leads to considerable complexities in associated modelling, especially in comparison to composite based on non-woven reinforcement,[1]. The forming of textile preforms requires knowledge of the structure of yarn and fibers. Yarns are linear assemblages of fibers formed into continuous strands having textile characteristics, i.e. substantial strength and flexibility. A fabric is a collection of fiber yarns arranged in a given pattern.

2.2 Woven fabrics structure

Woven fabrics, formed on a loom by interlacing two or more sets of yarns, are:

- *biaxial* constructions, made from two sets of yarns which interlace, essentially at 90^0 (orthogonal woven fabrics), exhibit good dimensional stability in the two directions. They exhibit a good dimensional stability in the warp and fill (or weft) directions and offer highest cover on yarn packing density.

- *triaxial* woven, made from three sets of yarns which interlace at 60^0 , provide higher isotropy and in-plane shear rigidity than orthogonal woven

An *orthogonal two-dimensional* (2D) woven fabric consists of two sets of interlaced yarns. The lengthwise set is called warp, and the crosswise set, fill (weft). Any weave repeats on certain number of warp and fill yarns. The repeat is a complete representative *unit cell* of weave. The regions enclosed by the dotted lines define the “*unit cells*” or the basic repeating regions for different weaving patterns [2,3,7]. Different types of weaves can be identified by repeating patterns in both directions, defined by geometrical quantities n_w, n_f . The number n_f denotes that the warp yarn is interlaced with every n_f filling yarn and n_w denotes that a fill yarn is interlaced with every n_w -th warp yarn. [2,3,7].

The fabric geometry should be chosen so that it should give the best possible properties for the application under consideration. The important fabric parameters are *strands* cross-sectional geometry, *finesse*, *number of counts* and the weaving condition such as balanced or unbalanced. The *fabric counts* is the number of yarns (strands) per unit length along the warp or fill direction. *Linear density* of the yarn is defined as weight per unit length, which is a measure of finesse of the yarn and is given by the tex number [g/km]. The *yarn crimp* is a measure of the degree of undulation. The undulated length within the interlacing region is termed “*u*”. A plain weave fabric can be *balanced* or *unbalanced* depending upon the number of counts and yarn properties. If the yarn properties such as cross-sectional geometry, tex, crimp, the number of counts and the material properties are the same in both directions (warp and fill) the fabric is called balanced fabric. The unbalanced fabric can be used if different properties are required along the warp and fill directions, [2,3,6]. The (termo-) elastic behavior of woven composites depends on the type of *weave fabric geometry*, *fiber volume fraction*, *laminare configuration* and the material system used.

2.3 Lamina configuration

In the present work, the analysis is restricted to nonhybrid two-dimensional (2D) orthogonal unbalanced plain weave fabric lamina, illustrated in Fig. 1.

The idealized representation plain weave fabric lamina is presented in Fig. 1. So, the unit cell consists of the interlacing region and the gap region. The interlacing region consists of the warp and fill yarns one over the other. For this cell, the main geometrical parameters are:

- ⇒ yarn width = a_w (a_f); ⇒ undulated length = u_w (u_f);
- ⇒ yarn thickness = h_w (h_f); ⇒ fabric thickness = h ;
- ⇒ interyarn gap = g_w (g_f); ⇒ lamina thickness = h

A unit cell of plain weave fabric lamina used in this analyze is shown in Fig. 1. The sections at the boundaries of the unit cell are also shown.

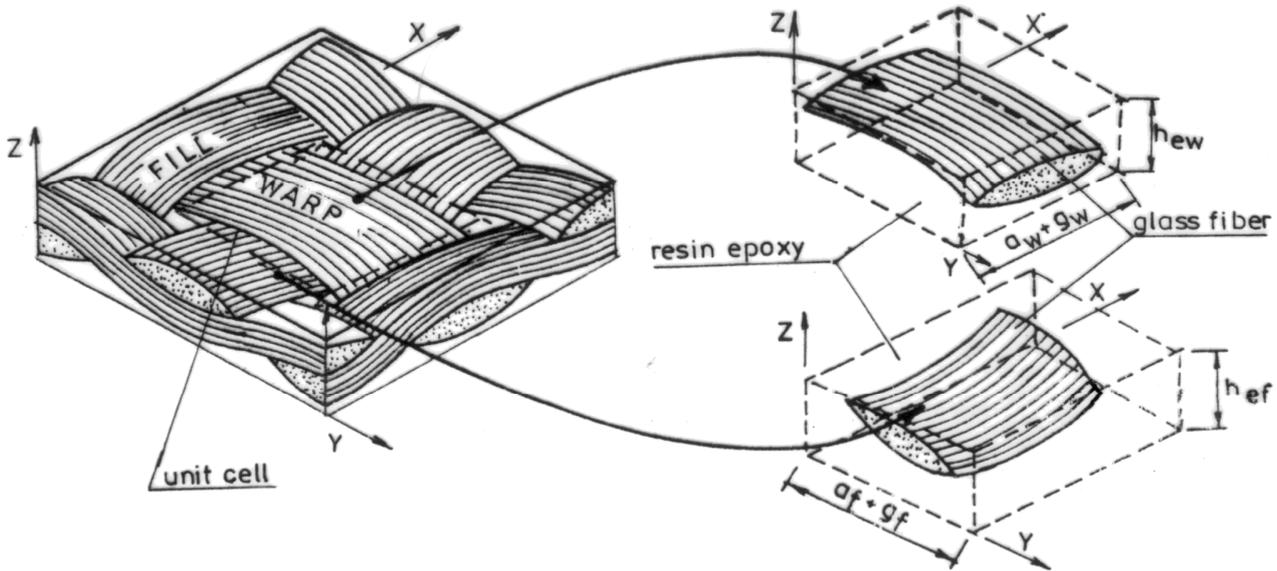


Fig. 1. The unit cell used for analysis.

Knowing the fabric counts (n_1 = warp yarn counts and n_2 = fill yarn counts) we have calculated the equivalent thickness for each other UD ply, [1].

$$h_{e/w} = h n_1 / (n_1 + n_2) = h k_1 \quad h_{e/f} = h n_2 / (n_1 + n_2) = h k_2 \quad (1)$$

where:

h = thickness of lamina

h_f = thickness of UD ply which have the fibers on fill direction

h_w = thickness of UD ply which have the fibers on warp direction

k_i = the relative volume fraction of the i -th reinforcing system

Assuming that the fibers are aligned along the x -axis for one ply and for the other are aligned along y -axis, each UD ply present orthotropic symmetry in the x - y plane. The stiffness constants $C^{w(f)}$ of each UD-ply were determined using Tsai-Hahn algorithm, [8]. Then, with the *stiffness averaging*, we have calculated the global composite stiffness matrix C_{comp} .

$$C_{comp} = k_1 C^w + k_2 C^f \quad (3)$$

Knowing the stiffness matrix or compliance matrix, we have obtained the elastic constants of composite : E_x , E_y , G_{xy} , ν_{xy} :

$$E_x = \frac{C_{11}}{H} \quad E_y = \frac{C_{22}}{H} \quad G_{xy} = C_{66} \quad \nu_{xy} = \frac{C_{21}}{C_{22}}$$

$$H = \left(1 - \frac{C_{12}}{C_{11}} \cdot \frac{C_{21}}{C_{22}} \right)^{-1} \quad (4)$$

4. Results

In order to exploit the genetic algorithm based optimization method for woven composite, we have chosen a material with the following elastical and geometrical properties.

In order to validate the results we have compared the values of the elastic constant E_y , obtained after optimization with those obtained theoretically and experimentally using the averaging stiffness matrix method. The experimental average (range) for the *Young's modules for unbalanced plain weave fabric lamina* are 14.8 (14 -22) GPa and predicted value using the averaging stiffness matrix method is 20.51 GPa,[2,3,6]

Due to the fact that undulation of fibers, dimensions of gap between the warp and fill yarn, lamina thickness and the nature of matrix can change the values of elastic characteristics, we have selected these parameters as variables for the Young modulus E_y (on warp direction) optimization process.

Table 1. Elastic properties of fiber and resin.

Material	E_l (GPa)	E_t (GPa)	G_{tl} (GPa)	G_{tt} (GPa)	ν_{tl}	ρ_g /cm ³
glass -E	72.0	72.0	27.7	27.7	0.30	2.58
epoxy resin	3.5	3.5	1.3	1.3	0.35	1.17

Table 2. Yarn and fabric geometry ($u/a=1, h_u=h_b=h/2$).

Fabric material	Fabric thickness h_t (mm)	Counts/cm		Width of yarn		Gap		Fabric weight
		w	f	a_w	a_f	g_w	g_f	
(a) glass-E	0.50	6.40	5.80	1.44	1.12	0.12	0.60	470 g/m ²

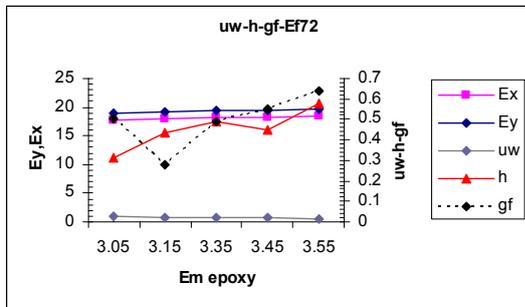
Table 3. Properties of plain weave fabric lamina.

Material system material / material	Fabric thickness h_t (mm)	Lamina thickness h (mm)	Overall fiber volume fraction
glass-E / epoxy	0.50	0.50	0.39

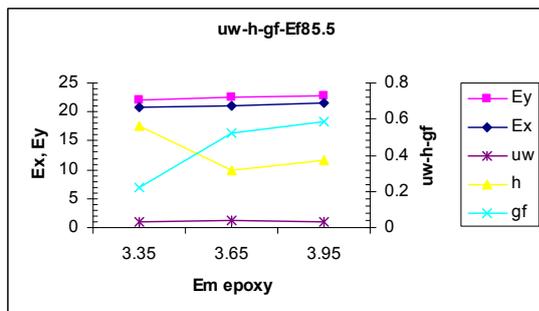
So, in the first case, the we have selected undulation on warp direction, thickness of lamina and the value of gap on fill direction. Fig. 2 a) presents E_y optimized for glass fiber with $E_f=72$ GPa and different values of the elastic modulus of epoxy matrix, while in Fig. 2 b) presents the case of glass fiber with $E_f=85.5$ Gpa is illustrated.

In the second case, presented in Fig. 3, the chosen parameters are undulation on both direction (warp and fill direction) and the thickness of lamina for epoxy matrix and glass fibers with $E_f=72$ GPa.

The third case, from Fig. 4.,considers undulation on fill direction, gap dimension on warp direction and thickness of lamina as optimizing parameters, for epoxy matrix and glass fibers with $E_f=72$ GPa.



(a)



(b)

Fig. 2. Young' modulus E_y optimized in the case of variables (uw-h-gf); a) glass fiber $E_f=72$ GPa; b) glass fiber $E_f=85.5$ GPa.

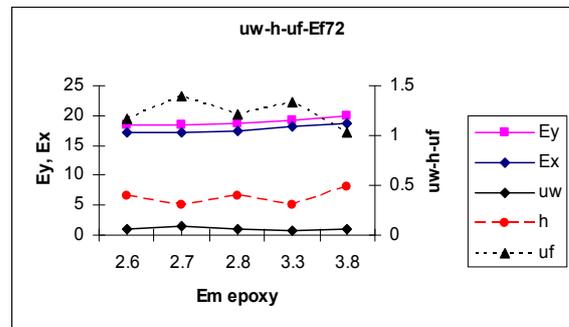


Fig. 3. E_y optimized considering the variables (uw-h-uf).

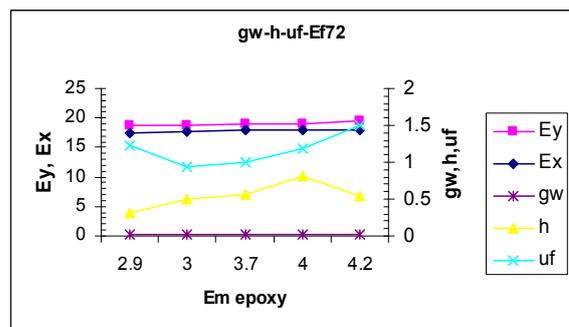


Fig. 4. E_y optimized considering the variables (gw-h-uf).

5. Conclusions

Due to the complexity of all these materials, the design of fabrics or composites reinforced with fabrics demands developing of new computational methodologies to determine the elastic constants (as closed to the experimental values) and their optimization. The fabric geometry should be chosen so that it should give the best possible properties for the application under consideration. The paper presents only lamina level optimization. The authors intend, based on the obtained results, to develop laminate optimization. Investigating the analytically obtained results one can observe that they agree with the experimental ones [3], [6]. This fact validates both the computing methodology and the optimization procedure.

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