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IMECE2010-38761

COMPOSE-IT: A COMPUTER-BASED TOOL FOR THE DESIGN AND OPTIMIZATION OF COMPOSITE LAMINATES

Ramsey F. Hamade

American University of Beirut
Mechanical Engineering Department
P.O. Box 11-0236, Riad El-Solh
Beirut 1107 2020, Lebanon
Email: rh13@aub.edu.lb

Ali H. Ammouri

American University of Beirut
Mechanical Engineering Department
P.O. Box 11-0236, Riad El-Solh
Beirut 1107 2020, Lebanon
Email: ahe11@aub.edu.lb

Abstract

Compose-it is a software tool developed to aid users in the design of composite materials. This tool allows the user to input functional requirements associated with the composite structure and its loading. The software tool has a user-friendly graphical user interface which leads the user through the various phases of design and optimization of composites. While the analysis is based on the classical laminated plate theory, several special boundary conditions are incorporated to allow for out-of-plane loading and mixed boundary condition scenarios. The tool accepts many input variables relating to materials (fiber and matrix), material anisotropy, ply thickness, orientation, stacking sequence, and symmetry and special layups. Output includes stress, strains, stiffness, and deflections for optimized ply stack-ups. Simulated annealing optimization technique is incorporated so that the user can compare different 'optimum' solutions for desired criteria such as design for maximum in-plane stiffness or maximum in-plane strength.

Keywords:

Software tool, laminate design, multi-objective optimization, simulated annealing, smart prompter

1. INTRODUCTION

Compose-it is a Windows based application developed using the National Instruments LabVIEW [1] software. When compared to classical educational analysis software (e.g. PROMAL [2]), Compose-it provides several advantages including (1) user-friendly interface and (2) intelligent design features (based on the simulated annealing optimization technique) for finding solutions of composite design problems. The tool utilizes a user-friendly tool for the analysis and optimized designs of composite laminates. This tool can be used by novice students learning the basics of composite mechanical analysis as well as by seasoned designers to explore the intelligent, customized abilities of composite materials. Materials properties inputs are allowed either as (1) input by the user if the properties are known or (2) are calculated according to micromechanical models. In the analysis mode, macro-mechanical analyses of a single lamina or a laminate can be run. The ease of use of the software renders it useful for novice users (students) because it will help them operate at various levels from working out simple exercises, such as finding local and global stresses in a lamina, all the way to exploring different output solutions based on differences in the predefined inputs. In the optimization mode, complex tradeoffs are explored depending on whether the user is interested in in-plane strength, in-plane stiffness, and/or out of plane deflection of the composite laminate. Thus, embedded artificial intelligence (AI) features allow

advanced users to utilize Compose-it in a fashion that complements their existing design knowledge.

2. COMPOSE-IT DESCRIPTION

Although comparable tools exist (e.g., [3]), Compose-it is characterized by several unique features including:

1. Smart prompter: interacts with the user to ask/help in the design/analysis of the composite laminate.
2. Use of multi-objective functions in the simulated annealing optimization with the ability to choose among several optimization cost functions during the design of the laminate specifically: weight/geometry, stiffness, and out-of-plane deflection.
3. Smart switching between the analysis and optimization modes of the software.

These features are detailed thereafter.

2.1 Software Overview

Figure 1 is a flowchart of the Compose-it software. It illustrates the interaction between the user and the smart features of the software along with the algorithm followed during the data input and optimization stages. The Compose-it graphic user interface (Figure 2) is divided into four areas: the user input area, the laminate stack display, the results display area, and the smart

prompter. The user input along with the smart prompter are used to input the known parameters of the laminate while the stack display area and the results area are used to display the outcomes of the laminate being studied.

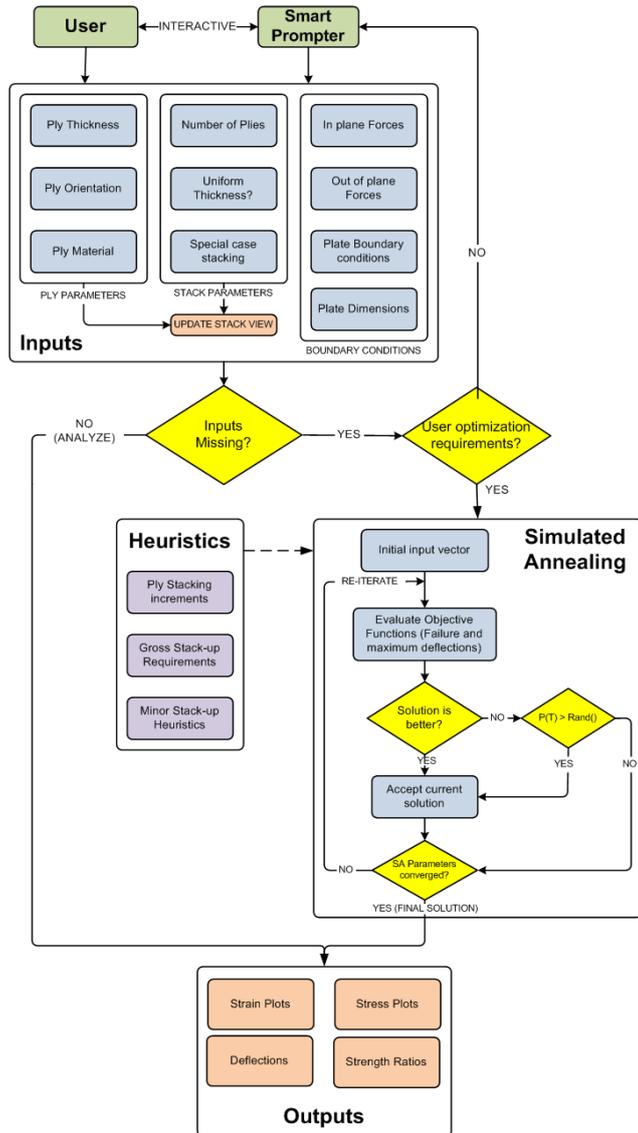


Figure 1. Compose-it flowchart diagram

The user input area consists of three tabs: Material/Stack, Forces/BCs, and Results. By default, when Compose-it is launched, it starts with a single ply lamina in the analysis mode. If the number of plies is changed to another integer value, the software will automatically build a laminate with the default material, thickness and orientation. The stacking layout can be constrained by selecting special cases of stacking sequences from the selection tab near the number of plies. Also uniform ply thickness checkbox can be checked to disable the user from changing the individual ply thickness in the laminate stack.

2.2 The Material/Stack Tab

Individual lamina parameters, such as thickness, orientation, and material can be changed from the laminate indexer in the material/stack tab also. Figure 2 shows a 3 ply lamina with uniform thickness and [0/30/45] stacking sequence. The lamina material can be selected from the existing material database (Table 1).

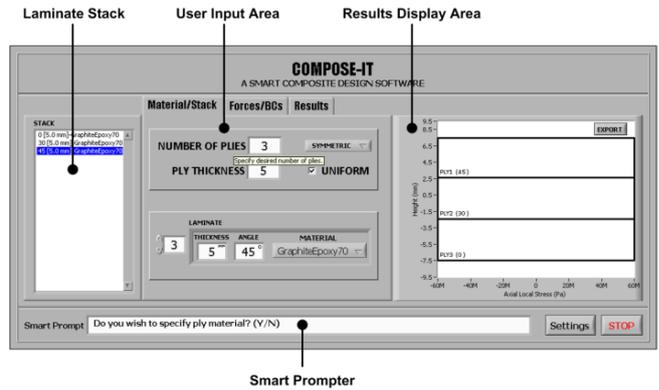


Figure 2. Compose-it GUI. Shown is the material/stack tab for the user input.

If the user wishes to create a new material that doesn't exist in the database with custom fiber/matrix material and volume fraction, s/he can do so by selecting "Custom" material from the material selection tab in the laminate parameters to go directly to the material database manager.

Table 1. Existing Material Database	
Graphite Family	Glass Family
AS4/APC2	E-Glass/Epoxy
CFS003/LTM25	S-Glass/Epoxy
IM6/Epoxy	GE 7781/5245C
GY70/934	
IM6/SC1081	
Mod I/WRD9371	
MR50/LTM25	
NAS-S/NCT321	Aramid Family
T300/5208	Kevlar 149/Epoxy
T300/934	

The material database manager (Figure 3) is a tool that can be used to update existing material database and to create new custom material. The creation of new material is done by using micromechanical models. The method of calculating the generated material can be selected from the list-box in the material manager window.

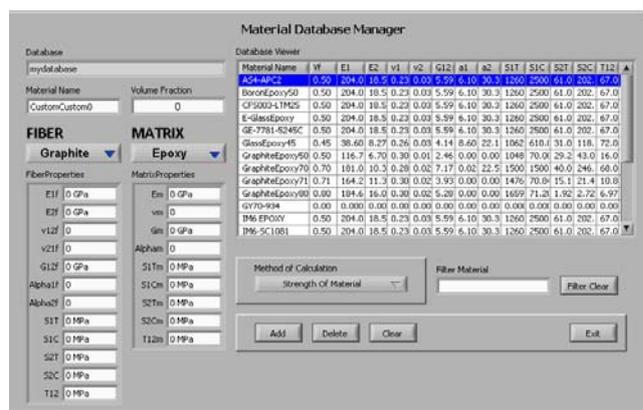


Figure 3. Material database manager window. Example shown is for Graphite/Epoxy AS4/APC2

Figure 4 shows the second tab in the user input area: the Forces/BCs tab. Here the user is prompted to input the in-and out-of- plane forces (along with the optional plate boundary conditions and dimensions).

The screenshot shows the 'Forces/BCs' tab of a software interface. It is divided into several sections:

- In-Plane Forces:** Six input fields for N_x , N_y , N_{xy} , M_x , M_y , and M_{xy} with units N/m or Nm/m. Values are mostly 0 or 1k.
- Boundary Conditions:** A checkbox and four dropdown menus for Left, Right, Top, and Bottom, all set to 'Clamped'.
- Out of Plane Forces:** Two input fields for P (MPa) and F (N), both set to 0.
- Plate Dimensions:** Two input fields for W (mm) and L (mm), both set to 0.
- UPDATE:** A button at the bottom left.

Figure 4. Forces/BCs tab of the user input area

The third tab in the user input area is the results tab where stresses, strains, and deflections can be visualized on the Results display area as plots and/or exported to a text file for storing the analysis data. While working with the user input area, the Laminate Stack tree is updated automatically to show the current laminate stack.

2.3 The Smart Prompter

The smart prompter is a novel feature in Compose-it that adds intelligent composite design capabilities. It is an interactive feature that provides help in the design process of composite laminates by asking questions during the data input by the user. It also provides hints to facilitate the understanding of the different parts of the software. The mode of operation of the software can be switched between analysis and optimization based on the user response to the smart prompter.

Switching to the optimization mode can be determined by one of the followings:

1. If the user doesn't wish to specify some of the laminate parameters (angle, thickness, orientation).
2. If the user responds to the smart prompter that s/he needs help in the laminate design.
3. If the user switches to the Results tab without providing some input parameters.

These modes of operation of the software will be discussed in details in the next Section.

3. MODES OF OPERATION

The software can be operated in two modes while using the same user interface. This is determined by the combination of user inputs and the response to the smart prompter.

3.1 Analysis mode

In the analysis mode of operation the user inputs all the laminate parameters that include the number of plies, individual ply thickness orientation and material. Afterwards the user switches to the forces/BCs tab to input all the in-plane or out-of-plane forces that are acting on the laminate. This ensures that the software has all the required inputs needed to calculate the local and global stresses and strains as well as the out-of-plane deflections (if out of plane loads were included) using the

classical mechanics theory of laminates. The smart prompter in this mode provides hints for the designer such as advising on the stacking special cases and shows tips for heuristics-based good laminate design rules.

3.2 Optimization mode

If the user switches to the results tab without providing some inputs (resulting in missing parameters such as laminate thickness or material), the smart prompter will ask the user if s/he needs to input missing data or optimize for the missing parameters.

Optimization is done using several objective functions and based on the user interaction with the smart prompter. The three objective functions utilized are:

1. Minimizing laminate's weight/thickness (subject to in-plane loads). This criteria is synonymous with ply strength.
2. Maximizing laminate's in-plane longitudinal stiffness or torsional stiffness (subject to in-plane loads)
3. Minimizing laminate's out of plane deflection (subject to out-of-plane load)

The first objective function aims to find the minimum number of plies from the selected material(s) database library that will not fail under the selected input forces (hybrid stack-ups allowed). The search space for the optimization technique will be limited by the amount of constraints that the user specifies. This depends on the level of knowledge the user has with the composite materials.

The method of failure can be selected by the user from a list of available failure theories along with the desired strength ratio of the laminate. The equation governing the first objective function is

$$\text{Minimize } f_1(N, m_i, \theta_i, t_i) = SR \quad (1)$$

where N is the number of plies, $(m_i / \theta_i / t_i)$ are the material, angle, and thickness of each ply, and SR is the strength ratio of the selected failure criterion. The ply strength dictates the laminates thickness and overall weight. We should note that the optimization variables can be modified if the user wishes to constrain it.

The second objective function is to maximize the stiffness of the overall laminate in a certain direction (i.e., longitudinal E_x , transverse E_y , and shear G_{xy} modulus). This is described by

$$\text{Maximize } f_2(N, m_i, \theta_i, t_i) = S \quad (2)$$

Where S is the stiffness (longitudinal or shear) modulus and the input variables are the laminate parameters as in (1). Such a representative S parameter is the longitudinal modulus as described by

$$S = E_x = \frac{1}{hA_{11}} \quad (3)$$

where A_{11} is the first element of the $[A]$ extensional stiffness matrix.

The software accommodates loading situations to which analytical closed form solutions exist such as a simply supported plate under uniform pressure. q_0 . Therefore, the third objective function deals with minimizing the out of plane deflection of the plate under out-of-plane loading. The equations governing the out-of-plane deflection will be selected according to the boundary conditions selected by the user and the type of loading force (for now only two options are available: uniform pressure and center force). Thus the third objective function is described by

$$\text{Minimize } f_3(N, m_i, \theta_i, t_i) = w \quad (4)$$

where w is the out-of-plane deflection of the plate and the variables are the laminate parameters. Once again these variables can be limited according to the user choice. An example of the deflection equation for a simply supported plate under uniform pressure is described by

$$w = \frac{16q_0}{\pi^6} \sum_{m=1,3,\dots} \sum_{n=1,3,\dots} w_{mn} \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right) \quad (5)$$

Where

$$w_{mn} = \frac{1}{mn} \left[D_{11} \left(\frac{m}{a}\right)^4 + 2(D_{12} + 2D_{66}) \left(\frac{mn}{ab}\right)^2 + D_{22} \left(\frac{n}{b}\right)^4 \right]^{-1}$$

(6)

The user can select a combination of the three objective functions (Figure 5) and based on the user selection, the global optimization cost function will be the minimization of the combination of the sub-objective functions.

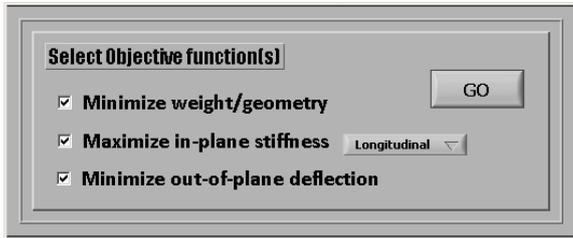


Figure 5. Optimization objective functions.

The global optimization function that will be used in the simulated annealing is defined as:

$$\text{Minimize } E = \sum (f_i - f_d)^2 \quad (7)$$

Where E is the least square error, f_i is the sub-objective function, and f_d is the desired value of the selected sub-objective function.

This objective function is passed to the simulated annealing optimization technique for finding the optimum values that will satisfy this global multi-objective cost function.

During the optimization process, a series of rules and heuristics are followed. The user is asked by the smart prompter on which rules to follow and based on the user response; the optimization process will be driven accordingly. These rules are summarized below:

1. Pre set angle increments of 15 degrees is used

2. Gross stack up options:
 - a. Symmetric stack up to uncouple forces and moments
 - b. Cross ply stack up to uncouple normal and shear forces.
 - c. Angle ply laminate stack up for high shear strength and stiffness
 - d. Anti-symmetric laminate stack up to uncouple extensional and bending stiffness
 - e. Balanced laminate stack up to uncouple extensional stiffness
 - f. Quasi-isotropic laminate stack up for an isotropic-like material behaviour.
3. Additional ply stack up heuristics as recommended in [3]:
 - a. Homogeneous lay-ups are recommended for strength controlled design.
 - b. Minimize groupings of plies with same orientations to create a more homogeneous laminate and to minimize inter-laminar stress and matrix cracking during the service period.
 - c. Avoid grouping of 90° plies and separate 90° plies by a 0° or 45° ply to minimize inter-laminar shear and normal stress.
 - d. Separate $\pm\theta$ plies to reduce inter-laminar shear stress.
 - e. Shield primary load carrying plies by positioning inside of laminate to increase tensile strength and buckling resistance

Based on the user response to the smart prompter, these rules will drive the optimization process. This is translated via limiting the optimization space by constraints desired by a knowledgeable user while keeping a wide space of optimization variables that are driven by design heuristics for a novice user.

4. OVERVIEW OF SIMULATED ANNEALING

Several available optimization techniques such as the Genetic Algorithm, Ant Colony search, Tabu search, and Simulated Annealing search are based on random search techniques and are all used in engineering optimization problems. Each method of optimization follows a guided-random-search mechanism which will most likely yield to an optimum solution. In the current paper, Simulated Annealing is used [4].

It simulates the softening process (annealing) of metals. In the annealing process the metal is heated-up to a temperature near its melting point and then slowly cooled-down. This allows the particles to move towards an optimum energy state, with a more uniform crystalline structure. The process therefore permits some control over the microstructure.

An Optimization problem can be visualized as a geographical terrain with many valleys and hills. The valleys represent the local minima with only one global minimum. The optimization technique needs to find this global minimum. SA approaches this problem similar to using a bouncing ball that can bounce over mountains from valley to valley.

The algorithm starts at a high "Temperature", where the temperature is a SA parameter that mimics the effect of a fast moving particle in a hot object like a hot molten metal, thereby permitting the ball to make very high

bounces and being able to bounce over any mountain to access any valley given enough bounces. As the temperature is made relatively colder, the ball cannot bounce so high, and it also can settle to become trapped in relatively smaller ranges of valleys. When the temperature freezes, the ball settle in the last valley reached. This will be the Global minimum of the given cost function.

On each step, the temperature must be held constant for an appropriate period of time (i.e. for an appropriate number of iterations) in order to allow the algorithm to settle into a thermal equilibrium, i.e. a balanced state. If this time is too short, the algorithm is likely to converge to a local minimum. The combination of temperature steps and cooling times is known as the “Annealing schedule”, which is usually selected empirically.

The artificial temperature (or set of temperatures) acts as a convenient stochastic source for eventual de- trapping from local minima. Near the end of the process the system hopefully is within the attractive basin of the global minimum. The challenge is to cool the temperature as fast as possible and still have the guarantee that no irreversible trapping at any local minimum has occurred. More precisely, we search for the quickest annealing (approaching a quenching) which maintains the probability of finishing within the global minimum equal to one [5].

From a given initial solution the algorithm randomly finds a neighbor by changing one of the parameters. This new solution is checked for the error. If it is better than the previous solution it will directly replace the old one. If the fitness of a new trial solution is less than the fitness of the current solution, the trial solution is not automatically rejected. Instead it becomes the current solution with a certain transition probability, $P(T)$, which depends on the difference in fitness and the temperature. By this way the algorithm will escape from the local minima. Here temperature is an abstract control parameter for the algorithm rather than a real physical measure. The transition probability, $P(T)$, for a given temperature and a given difference in fitness ΔF can be determined as follows:

$$P(T) = e^{-\frac{\Delta F}{T}} \tag{8}$$

The new temperature will be $T = \alpha T$ where α is a number which is less than 1. The algorithm will stop if: 1) the temperature freezes, 2) The error reaches its minimum value, 3) The maximum number of iterations is violated. Figure 6 is a flow chart illustrating the Simulated Annealing algorithm. Many factors of this algorithm can be modified to get several versions of the Simulated Annealing procedure. These factors are problem dependent and cannot be generalized for all optimization problems. The general terms used in the algorithm varies from one optimization problem to another depending on the type of the problem.

Note that the optimization tuning parameters can be predefined by pressing the settings button on the main menu of the software (Figure 7).

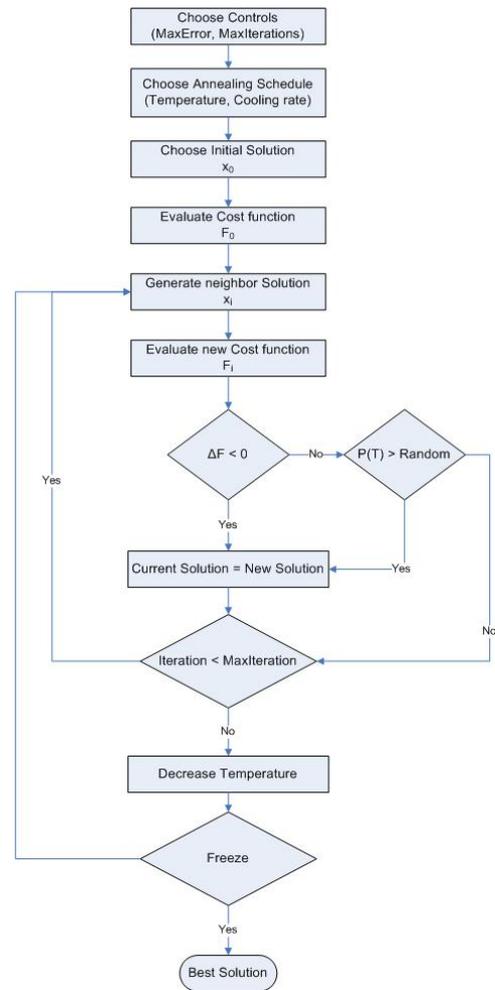


Figure 6. Simulated Annealing algorithm

5. RESULTS AND VALIDATION

Compose-it was validated by the following two examples:

1. Analysis validation problem [2; example 4.35, page 335]
2. Optimization validation problem [6]

5.1 Analysis validation

In the first problem, we are required to find the local and global stresses in a [0/30/-45] graphite/epoxy laminate subject to a load of $N_x=N_y=1000$ N/m with a uniform ply thickness of 5mm.

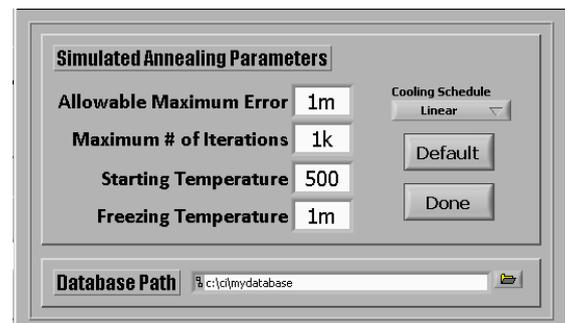


Figure 7. Setting window of the software

Since all the inputs are given, the number of plies (3) is input in the material/stack tab with 5 mm as the ply thickness and checking the uniform check box. This will create a [0/0/0] laminate that is shown in the stack view and in the plot area as 3 ply laminate. The angle for each ply is input through the main window by clicking on each ply and selecting the corresponding ply orientation and material.

The next step is to go to the forces/BCs tab and inputting 1000N for both N_x and N_y . When the value of the force array is changed, the new stresses/strains are automatically calculated. The results are shown by going to the results tab and hovering mouse over the plot you want to see. The result automatically appears in the plot to the right. In the example, the variation of the axial local stresses along the laminate thickness is shown Figure 8.

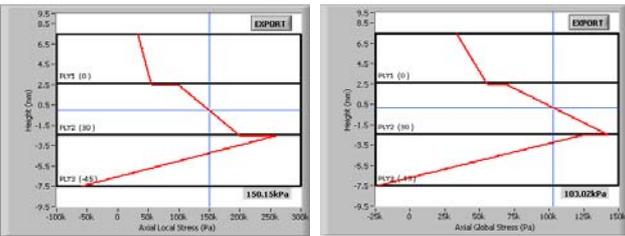


Figure 8. Axial local and global stresses (corresponds to example 4.35, [2])

The resultant mid-plane stress (150.15kPa) is the same result that was calculated in [2]. The remaining local and global stress and strain plots can also be visualized and the results were found to be identical. Table 2 summarizes the local stresses throughout selected heights in the laminate that corresponds to Figure 8.

Table 2. Local Stresses (Pa) in [2; Example 4.3]

Ply no	Position	σ_1	σ_2	σ_{12}
1(0°)	Top	3.351×10^4	6.188×10^4	-2.750×10^4
	Middle	4.464×10^4	5.359×10^4	-2.015×10^4
	Bottom	5.577×10^4	4.531×10^4	-1.280×10^4
2(30°)	Top	9.973×10^4	4.348×10^4	1.890×10^4
	Middle	1.502×10^5	3.356×10^4	1.702×10^4
	Bottom	2.007×10^5	2.364×10^4	1.513×10^4
3(-45°)	Top	2.586×10^5	2.123×10^4	-1.638×10^4
	Middle	9.786×10^4	2.010×10^4	-9.954×10^3
	Bottom	-6.285×10^4	1.898×10^4	-3.533×10^3

5.2 Optimization validation

The second validation problem is an optimization problem adopted from [6]. In this problem a plate of 100x100 mm dimensions is subject to a uniaxial loading. The total number of plies of the laminate is 16 and the composite laminate considered is made of HFG CU-125NS graphite/epoxy. The optimization problem is to maximize the strength of composite laminates for a given layer thickness, the design variable is the ply orientation angle.

Since the material is not included in our library, we first created a new material using the material database manager.

The known inputs (number of plies, ply material) and constraints, angle restrictions are input using the Compose-it controllers and smart prompter. The only variable to optimize for is the stacking sequence. The

cost function used is f_1 and the simulated annealing default parameters are used (number of iterations: 1000, starting temperature: 500, freezing temperature: 0.001 and maximum allowable error of 0.001).

The outcomes of the optimization process was a [0/0/0/0/0/0/0/0]_s stack which is the same result found by [6]. Subject to uniaxial loading, the global minimum of the optimization function results only when the fibers are aligned with the loading force (the 0 direction). When adding the design heuristics rule constraints to the optimization problem, once again the solution is identical to what is gotten by [6] which is a [0/0/0/0/90/0/0/90]_s laminate. This is due to the 3b rule from the heuristic table listed in section 3.2

6. SUMMARY

Composite-It is a combined analysis/optimization software tool developed to aid in the design of composite laminates. The tool incorporates several novel, user-friendly features which makes it useful for both the novice user as well as the seasoned designer. For advanced users, optimization techniques utilize the simulated annealing technique and allow for design according to three design criteria. Validation examples are presented for both analysis and optimization functions.

7. ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support of the University Research Board (URB) of the American University of Beirut. Also, the second author wishes to acknowledge the support of Consolidated Contractors Company through the CCC Doctoral Fellowship in Manufacturing.

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