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Laminated Composite Plate Optimization by Improved Genetic Algorithm

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Abstract

The main challenge presented by the design of laminate composite is the laminate layup, involving a set of fiber orientation, compoiste material system, and stacking sequence. In nature, it is a combinatorial optimization problem which can be solved by the genetic algorithm(GA), and the problem with the basic GA is weaker local search performance, and faster convergence speed. In this study, a mix selection strategy is suggested to introduce to the basic GA to prevent from premature and improve local search ability. To check the feasibility of a laminate under in plane load, the effect of fiber orientation angles and materials component on the first ply failure is also studied. A comparative study of basic GA and improved GA in composite laminate designing for a targeted safety factor is also studied. An optimum composite material and laminate layup is well developed for a targeted strength ratio which makes a compromise between weight and cost through improved genetic algorithm.

Keywords

Genetic Algorithm, Laminates, Stacking Sequence, Hybrid Composites

1. Introduction

Composite materials offer improved strength, stiffness, fatigue, and corrosion resistance, etc over conventional materials, which are widely used as materials ranging from automotive to ship building industry, electronic packaging to golf clubs, medical equipment to home building. However, the high cost of fabrication of composites is a critical drawback for its application, for example, the graphite/epoxy composite part may cost as much as $650 to $900 per kilogram, while the price of glass/epoxy is about 2.5 times less. Although manufacturing techniques such as sheet moldin compound and structural reinforcement injection molding are taken to lower the cost in manufacturing automobile parts, however, in this study an alternative approach is provided by using of hybrid compoiste materials.

The mechanical performance of a composite laminate is affected by a wide range of factors, thickness, material, and orientation of each lamina. Beause of manufacturing limitation, all these variables are usually limited to a small set of discrete values. For example, ply thickness are fixed and ply orientation angles are limited to a set of angles such as 0,45,90 degrees. So the search process for the optimal design is a discrete optimization problem which can be solved by genetic algorithm(GA). To tailor a laminate composite, GA has been successfully applied to solve laminate design problem[2,8,11,12,15,16,22,23,25,29,30]. GA simulates the process of natural evolutionary includes selection, crossover, and mutation according to Darwin's principal of "survival of the fittest". The known advantage of GA as the following: (i): GAs are not easily trapped in local optima, and be able to obtain the global optimal. (ii): GA doesn't need gradient information and can be applied to discrete optimization problem. (iii): GA not only be able to find the optimal value in the domain, but also can maintain a set of optimal solutions. On the other hand, GA also has some disadvantages, for example, the GA needs to evaluate the target functions a lot of times to achieve the optimization, the cost of the search process is high. The GA consists of some basic parts, the coding of the design variable, selection strategy, crossover operator, mutation operator, and how to deal with constraints. For the variable design part, there are two methods to deal with the representation of design variables, binary strings and real value representations[22,29]. Michalewicz[32] claimed the performance of floating point representation was better than binary representation in numerical optimization problem. Selection strategy plays a critical role in GA which decides the convergence speed and the diversity of the population. To improve search ability and reduce search cost, various selection methods have been invented, and it can be divided into four classes which are proportionate reproduction, ranking, tournament, and genitor(or "steady state") selection. In the optimization of laminated composite structure, roulette wheel[22,24], where the possibility of an individual to be chosen for the next generation is proportional to the it's fitness. Soremekun[28] showed generalized elitist strategy outperformed a single individual elitism in some special cases.

Data structure, repair strategies and penalty functions[10] are most common used approaches to resolve constraint problems in the optimization of composite structure. Symmetric laminates are widely used in practical scenario, data structure can be used to fulfil the symmetry constraint

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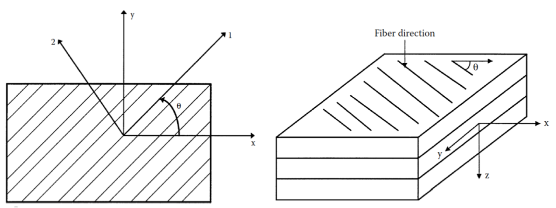

Figure 1. Lamina

which consists of coding a half of the laminate and considering the rest with the opposite orientation. Todoroki[29] introduced a repair strategy which can scan the chromosome and repair the gene on the chromosome if it does satify the contiguity constraint. The comparsion of repair strategies in a permutation GA with the same orientation was presented by Liu[12], and it showed the Baldwinian repair strategy can significantly reduce the cost of constrained optimization. Haftka[22] used GA to solve laminate stacking sequence problem using a penalty function subject to buckling and strength constraints.

In typical engineering applications, composite materials are under very complicate loading conditions, not only in-plane loads but also out-of-plane loads. Most of the studies on the optimization of laminated composite materials was to mimimize the thickness[1,30], weight[5,6,19], cost and weight[5,18], or maximize the static strength of composite laminates for a targeted thickness[9,11,30]. In the present study, laminate cost and weight are minimized by modifying the objective function.

In order to check the feasibility of a composite laminate by imposing a strength constraint, failure analysis of a laminate is taken by applying suitable failure criteria. The failure criteria of laminated composites can be classified in three classes: non-interactive theories(e.g., Maximum strain), interactive theores(e.g., Tsai-wu), and parially interactive theories(e.g., Puck failure criterion). The previous researchers adopted the first-ply-failure approach using the Tsai-wu failure theory[3,6,7,14,18,20,21,27], Tsai-Hill[13,26], the maximum stress[7,18], or the maximum strain[31] static failure criteria. Akbulut[2] used GA to minimize the thickness of composite laminates with Tsai-Hill and maximum stress failure criterias, and the advantage of this method is to avoid spurious optima. Naik[17] minimized the weight of laminated composites under restrictions with a failure-mechanism-based criterion based on Maximum Strian and Tsai-wu. In the present study, Tsai-wu static failure criteria is used to investigated the feasibility of a composite laminate.

2. Stress and Strain in a Laminate

A laminated structure is consisting of multiple laminas bonded together through their thickness. Consider a laminated composite plate which is symmetric to its middle plane and subjected to in-plane loads of extension, shear, bending and torsion, the classical lamination theory(CLT) is taken to calculate the stresses and strains in the local and global axes of each ply. as shown in Fig.1.

2.1 Stress and Strian in a Lamina

For a single lamina, the stress strain relation in the local axis: 1-2

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix}=\begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{12} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} \tag{1}$$

Where Q_{ij} are the stiffnesses of the lamina that are related to engineering elastic constants by

$$\begin{aligned}Q_{11}&=\frac{E_1}{1-v_{12}v_{21}}\\ Q_{22}&=\frac{E_2}{1-v_{12}v_{21}}\\ Q_{66}&=G_{12}\\ Q_{12}&=\frac{v_{21}E_2}{1-v_{12}v_{21}}\end{aligned} \tag{2}$$

Where, E_1, E_2, v_{12}, G_{12} are four independent engineering elastic constants, they are defined as

E_1 = longitudinal Young's modulus

E_2 = transverse Young's modulus

v_{12} = major Poisson's ratio

G_{12} = in-plane shear modulus

Stress strain relation in global axis: x-y

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix}=\begin{bmatrix}\bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16}\\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26}\\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix} \tag{3}$$

where

$$\begin{aligned}\bar{Q}_{11}&=Q_{11}c^4+Q_{22}s^4+2\left(Q_{12}+2Q_{66}\right)s^2c^2\\ \bar{Q}_{12}&=\left(Q_{11}+Q_{22}-4Q_{66}\right)s^2c^2+Q_{12}\left(c^4+s^2\right)\\ \bar{Q}_{22}&=Q_{11}s^4+Q_{22}c^4+2\left(Q_{12}+2Q_{66}\right)s^2c^2\\ \bar{Q}_{16}&=\left(Q_{11}-Q_{12}-2Q_{66}\right)c^3s-\left(Q_{22}-Q_{12}-2Q_{66}\right)s^3c\\ \bar{Q}_{26}&=\left(Q_{11}-Q_{12}-2Q_{66}\right)cs^3-\left(Q_{22}-Q_{12}-2Q_{66}\right)c^3s\\ \bar{Q}_{66}&=\left(Q_{11}+Q_{22}-2Q_{12}-2Q_{66}\right)s^2c^2+Q_{66}\left(s^4+c^4\right)\end{aligned} \tag{4}$$

The c and s denotes $cos\theta$, and $sin\theta$.

The local and global stresses in an angle lamina are related to each other through the angle of lamina θ

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix}=[T]\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix} \tag{5}$$

where

$$[T]=\begin{bmatrix}c^2 & s^2 & 2sc\\ s^2 & c^2 & -2sc\\ -sc & sc & c^2-s^2\end{bmatrix} \tag{6}$$

2.2 Stress and Strain in a Laminate

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{11} & B_{12} & B_{16} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix}$$
$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{11} & D_{12} & D_{16} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix} \tag{7}$$

N_x, N_y - normal force per unit length
N_{xy} - shear force per unit length
M_x, M_y - bending moment per unit length
M_{xy} - twisgint moments per unit length
ε^0, k - mid plane strains, and curvature of laminate in x-y coordinate

The mid plane strain and curvature is given by

$$\begin{bmatrix} \varepsilon^0 \\ k \end{bmatrix} = \begin{pmatrix} A & B \\ B & D \end{pmatrix}^{-1} \begin{Bmatrix} N \\ M \end{Bmatrix}$$

where

$$A_{ij} = \sum_{k=1}^{n} (\overline{Q_{ij}})_k (h_k - h_{k-1}) i = 1,2,6, j = 1,2,6$$
$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} (\overline{Q_{ij}})_k (h_k - h_{k-1}) i = 1,2,6, j = 1,2,6 \tag{8}$$
$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} (\overline{Q_{ij}})_k (h_k - h_{k-1}) i = 1,2,6, j = 1,2,6$$

The $[A]$, $[B]$, and $[D]$ matrices are called the extensional, coupling, and bending stiffness matrices.

3. Failure Theories

3.1 Failure Theories of an Angle Lamina

Many different theories about the failure of an angle lamina have been developed for a unidirectional lamina, such as maximum stress failure theory, maximum strain failure theory, Tsai-Hill failure theory, and Tsai-Wu failure theory. The failure theories of a lamina are based on the stresses in local axes in the material. There are four normal strength parameters and one shear stress for a unidirectional lamina. The five strength parameters are

$(\sigma_1^T)_{ult}$ = Ultimate longitudinal tensile strength,
$(\sigma_1^C)_{ult}$ = Ultimate longitudinal compressive strength,
$(\sigma_2^T)_{ult}$ = Ultimate transverse tensile strength,
$(\sigma_2^C)_{ult}$ = Ultimate transverse compressive strength, and
$(\tau_{12})_{ult}$ = Ultimate in-plane shear strength

In the present study, Tsai-wu failure theory is taken to decide whether a lamina is failed or not, the reason is chosen because this theory is more general than Tsai-Hill failure theory which consider two different situation, compressive and tensile strength of a lamina. A lamina is considered to be failed if

$$H_1\sigma_1 + H_2\sigma_2 + H_6\tau_{12} + H_{11}\sigma_1^2 + H_{22}\sigma_2^2 + H_{66}\tau_{12}^2 + 2H_{12}\sigma_1\sigma_2 < 1 \tag{9}$$

is violated. where

$$\begin{aligned} H_1 &= \frac{1}{(\sigma_1^T)_{ult}} - \frac{1}{(\sigma_1^C)_{ult}} \\ H_{11} &= \frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}} \\ H_2 &= \frac{1}{(\sigma_2^T)_{ult}} - \frac{1}{(\sigma_2^C)_{ult}} \\ H_{22} &= \frac{1}{(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}} \\ H_{66} &= \frac{1}{(\tau_{12})_{ult}^2} \\ H_{12} &= -\frac{1}{2}\sqrt{\frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}}} \end{aligned} \tag{10}$$

The Equation 9 can determine whether a lamina failed or not, but it fails to give the information about how much load can be increased or decreased to keep the lamina safe. The strength ratio(SR) is to used to solve this problem, and defined as

$$SR = \frac{\text{Maximum Load Which Can Be Applied}}{\text{Load Applied}} \tag{11}$$

Substituting Equation 11 for SR into Equation 9,we obtain

$$(F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + 2F_{12}\sigma_1\sigma_2)SR^2 + (F_1\sigma_1 + F_2\sigma_2)SR - 1 = 0 \tag{12}$$

3.2 Failure Theories of a Laminate

A laminate will fail under increasing mechanical, however, the procedure of laminate failure may not be catastrophic. In some cases, some layer fail first and the rest is be able to continue to take more loads until all the plies fail. a ply is fully discount when a ply fails, then the ply is replaced by near zero stiffness and strength. The procedure for finding the first ply failure in the present study follows the fully discounted method[4]:

1. Compute the reduced stiffness matrix $[Q]$ referred to local axis for each ply using its four engineering elastic constants E_1, E_2, v_{12}, and G_{12}.
2. calculate the transformed reduced stiffness $[\bar{Q}]$ referred to global coordinate system (x, y) using reduced stiffness matrix $[Q]$ obtained in step 1 and ply angle for each layer.
3. Given the thickness t_k and the location of each layer, find out the three laminate stiffness matrices $[A]$, $[B]$, and $[D]$.
4. Apply forces and moments, $[N]_{xy}$, $[M]_{xy}$, solve the equation 7, calculate the middle plane strain $[\sigma^0]_{xy}$ and cruvature $[k]_{xy}$.
5. Find out the local strain and stress of each layer under the applied load.
6. Use the ply-by-ply stresses and strains in Tsai-wu failure theory to find out the strength ratio.

4. Optimum Design of Laminate Composite

4.1 Genetic Algorithm

The GA starts off with a bunch of individuals with limited chromosome length, in which maybe none of these individuals fulfil the safety factor constraint. The GA are supposed to derive appropriate offspring based on initial population as the GA goes on. The classic way to handle constraint search of GA are either introducing repair strategies or using a penaly function, here a new approach is come up with to deal with constraint GA search problem by modifying the selection strategy.

Because of the existence of constraint, it means that the population not only can be sorted by fitness, but also can sorted by the constraint value obtained by the constraint function, so the parents of next generation can be chosen by these two approaches. First, sort out the population by the absolute difference between the individual's constraint value and the constraint threshold in an ascending order, and individual with smaller difference is more like to be chosen. Individuals obtained by this methods are called potential individuals. Second, sort out the population by fitness from low to high after remove the unproper individuals, and an individual is proper which means it fulfils the constraint, and individuals obtained by this way are called proper individuals. So the final parents consists of two parts, potential individuals and proper individuals.

The GA can be divided into two stages according to whether proper individual are generated during the search process

In the present study, the relevant parameters of GA are as shown in Table 1. The design variables are the materials, number of layers, and ply orientation restricted to a discrete set of angles ($0, \pm 45$ and 90 degrees). The possible materials are graphite/epoxy, caron/epoxy, and glass/epoxy and are represented by the codes 0, 1 and 2, respectively.

The selection method of the basic GA is sorting the population according to the absolute difference of individual's strength ratio and specified safety factor in an incresing order, individuals with smaller difference are more likely to be selected; However, because of premature and weak local search ability, basic GA are more likely to get stuck in local optimum. Therefore, to prevent the GA from early convergence and improve the local search performance, an improved GA is proposed by chosing individual according to fitness, ignoring whether the individual satisfy the constraint requirement. by combing basic GA existing selection strategy with this new selection approach, Individuals are selected from the two approaches forming the parents of next generation.

The laminate chromosomes are represented by double-gene string which can be divided into two parts, one part represents the angles, the other part represents the materials(as shown in Figure **??**). To maintain the diversity of the population, single-point crossover is taken during the evolution process. The break point in the string are chosen randomly, and one of the offspring of parent 1(as shown in Figure **??**) and parent 2(as shown in Figure **??**) is obtained by combining the gene segments $P1_o$ and $P2_o$, $P1_m$ and $P2_m$, respectively. The gene code of the offspring laminate is [+45, -45, -45, -45, -45, -45, -45, 0, 1, 0, 1, 1, 0, 1, 0].

To prevent the search from getting stuck in a local optimum, mutation is used to random change the gene in the chromosome, the offspring after mutation operator is as shown in Figure **??**

The GA is a stochastic procedure which heavily depends on the generator of pseudo random numbers. In the present study, the standard Wichmann-Hill generator is used in the algorithm, which combines three pure multiplicative congruential generators of modulus 30269, 30307 and 30323.

4.2 Design Problem I

The aim is to minimize the mass of a composite laminate for a targeted strength ratio by Tsai-wu failure theory. The design variable are the ply angles and the number of layers.

Find: $\{\theta_k, n\}$ $\theta_k \in \{0, +45, -45, 90\}$

Minimize: weight

Subject to: strength ratio and first ply failure constraint

4.3 Design Problem II

The aim is to mimimize the combined cost and weight of hybrid composite laminate under various loading cases, so the design variable not only include the ply angles and number of layers, but also the material of each lamina.

Find: $\{\theta_k, \mathrm{mat}_k, n\}$ $\theta_k \in \{0, +45, -45, 90\}$ $\mathrm{mat}_k \in \{CA, GR, GL\}$

Minimize:

$$F = \frac{\text{Cost}}{C_{\text{min}}} + \frac{\text{Weight}}{W_{\text{min}}} \tag{13}$$

Subject to: strength ratio and first ply failure constraint

Here CA, GF, and GL represent carbon/epoxy, graphite/epoxy, and glass/epoxy, C_{min} and W_{min} represent the cost and weight corresponding to the laminates with minimum cost and minimum weight obtained from previous problem.

5. Numberical Results and Discussion

A composite laminate with dimensions $1000 \times 1000 \times 0.165mm^3$ of each lamina is under various loading cases, and each CA, GF, and GL layer is assumed to cost 8, 2.5 and 1 monetary units, respectively. The other used material properties are as shown in Table 2. In the present experiment, the optimum composite system, layup, thickness, and number of layers for a targeted strength ratio(2 in this paper) under two different in-plane loading is investigated.

The GA process can be divided into two phases by whether there are individuals which are appropriate or not, an appropriate individual means it can satisfy the constraint. During the initial phase, no individual's strength ratio is over the specified threshold, so individuals with bigger fitness are more likely to be chosen as parents, that's why the strength ratio curves go all the way up to the specified threshold during the first stage; After the initial phase, the GA produces a bunch of appropriate individuals, and then the target function comes to play, as you can see from Fig.3, the fitness curves are trending to go down, but the strength ratio curves are keep to greater the specified threshold.

In the first experiment, the applied stress are $N_x = N_y = 1e6$ N. As shown in the Figure3, the Figure 3(a), (b),

Table 1. GA parameters

Parameter	Seed	Population size	LRIC	Encoding	Crossover Strategy	Mutation strategy
Value	1	10	[3-15]	Integer	One-point	Mass mutation

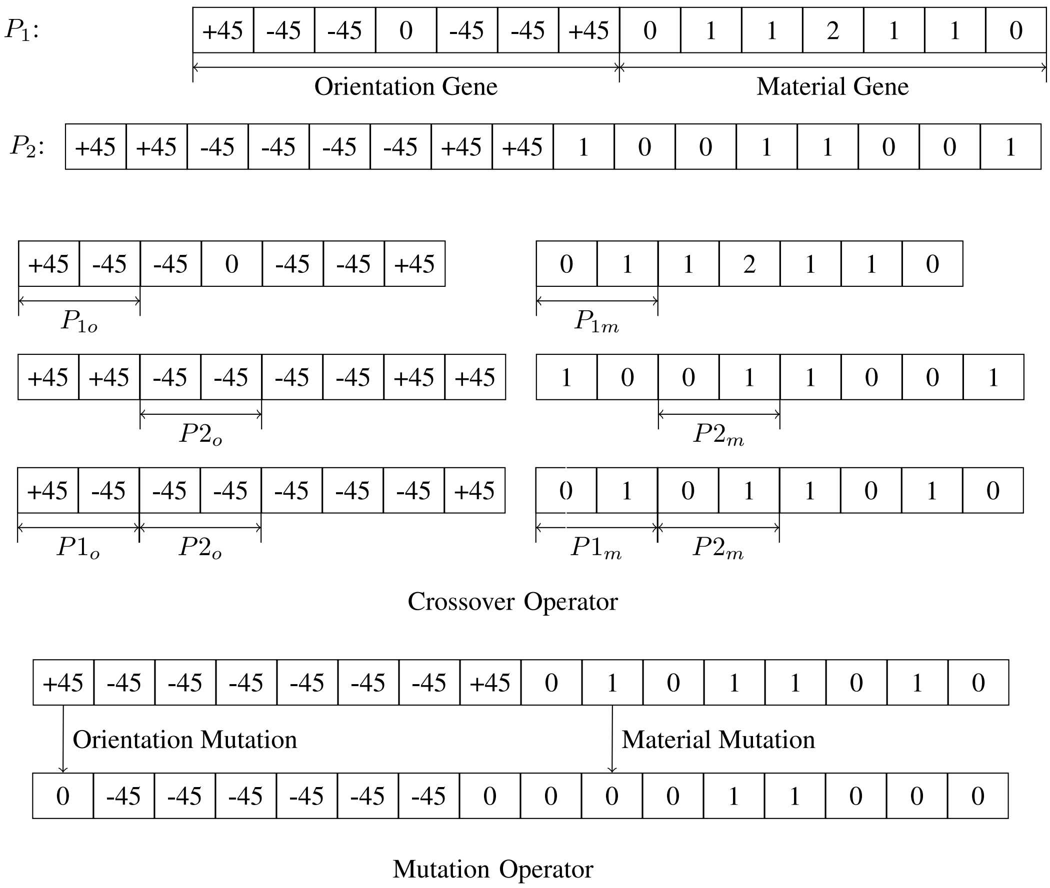

Figure 2. GA Operators

Table 2. Comparsion of carbon/epoxy, graphite/epoxy, and glass/epoxy properties

Property	Symbol	Unit	Carbon/Epoxy	Graphite/Epoxy	Glass/Epoxy
Longitudinal elastic modulus	E_1	GPa	116.6	181	38.6
Traverse elastic modulus	E_2	GPa	7.67	10.3	8.27
Major Poisson's ratio	v_{12}		0.27	0.28	0.26
Shear modulus	G_{12}	GPa	4.17	7.17	4.14
Ultimate longitudinal tensile strength	$(\sigma_1^T)_{ult}$	MP	2062	1500	1062
Ultimate longitudinal compressive strength	$(\sigma_1^C)_{ult}$	MP	1701	1500	610
Ultimate transverse tensile strength	$(\sigma_2^T)_{ult}$	MPa	70	40	31
Ultimate transverse compressive strength	$(\sigma_2^C)_{ult}$	MPa	240	246	118
Ultimate in-plane shear strength	$(\tau_{12})_{ult}$	MPa	105	68	72
Density	ρ	g/cm^3	1.605	1.590	1.903
Cost			8	2.5	1

Table 3. Optimization results

Load(N)	Problem	Algorithm	Stacking sequence	Strength ratio	Mass	Cost	Layer
	I	GA	$[\text{-}45_6^{cr}/\text{+}45_6^{cr}]_s$	2.026	1.271	192.0	24
	I	IGA	$[\text{-}45_6^{cr}/\text{+}45_6^{cr}]_s$	2.026	1.271	192.0	24
	I	GA	$[0_6^{gr}/\text{-}45_4^{gr}/\text{+}45_4^{gr}/90_7^{gr}/\bar{90}^{gr}]_s$	2.051	2.256	107.5	43
$N_x = 1e6$	I	IGA	$[\text{+}45_{10}^{gr}/\text{-}45_{10}^{gr}/\text{-}\bar{45}^{gr}]_s$	2.024	2.151	102.5	41
$N_y = 1e6$	I	GA	$[\text{-}45_{35}^{gl}/\text{+}45_{36}^{gl}/\text{+}\bar{45}^{gl}]_s$	2.001	8.980	143.0	143
	I	IGA	$[\text{-}45_{35}^{gl}/\text{+}45_{36}^{gl}/\text{+}\bar{45}^{gl}]_s$	2.001	8.980	143.0	143
	II	GA	$[\text{-}45_{12}^{gr}/\text{+}45_5^{cr}/\text{+}45_7^{gr}]_s$	2.141	2.523	175	48
	II	IGA	$[\text{-}45_9^{gr}/\text{+}45_9^{gr}/\text{-}45_2^{cr}/\text{+}45_2^{cr}]_s$	2.054	2.313	154	44

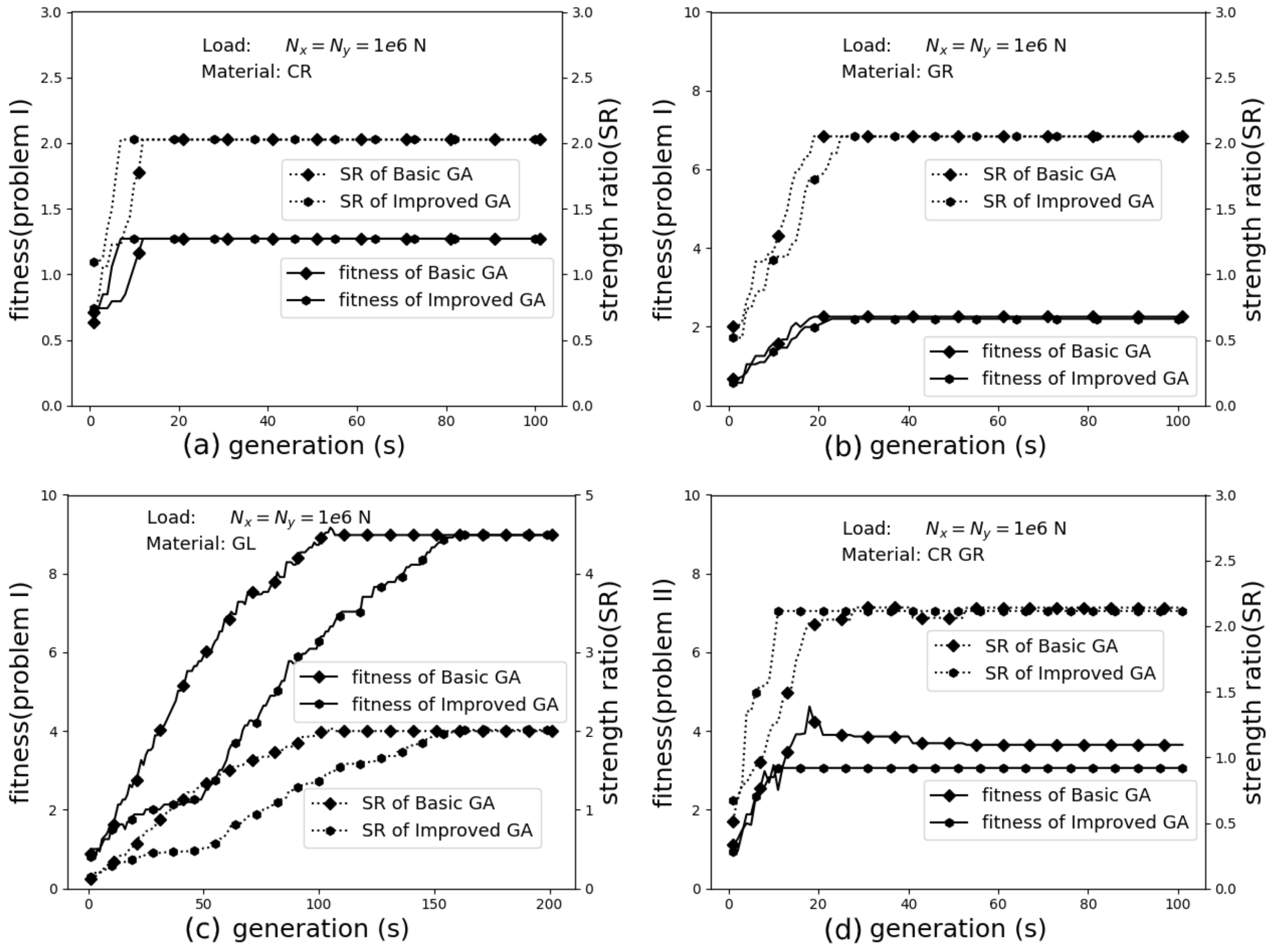

Figure 3. GA process under load $N_x = N_y$ = 1e6 N

and (c) were the experiment results for single material, Figure 3(d) is for hybrid composite material. For the single materials, both of the basic GA and improved GA method obtained the optimal value, but the improved GA converged more slowly than the basic GA. As it can be seen from Table 3, a $[-45_6/+45_6]_s$ carbon/epoxy laminate has the least weight, denoted by W_{min}, and a $[-45_{35}/+45_{73}/+45_{35}]$ graphite/epoxy laminate has the lowest cost, denoted by C_{min}. The W_{min} and C_{min} were used to evaluate the fitness of the second problem, which is the layup design of hybrid composite material , as shown in sub-figure d,the improved GA obtained a more appropriate system layup, whose strenght ratio is greater than the specified safety factor, and weight and cost is less than the result obtained by basic GA method, as shown in Table 3. Compared with basic GA, the improved GA method showed more powerful global search ability in the initial phase.

In the second case, the applied stress were $N_x = N_y = N_z = 1e6$ N, the experiment results were as shown in the Figure 4. In the first experiment, as can be seen from Figure 4(a), the improved GA got a better system layup then result obtained by basic GA; In the second experiment, as shown in the Figure4(b), during the initial phase, the fitness curves of basic GA and improved GA went all the way up to the previous specified threshold, however, the improved GA converged more slowly then the basic GA which means the search cost of improved GA is greater then basic GA. After the initial phase, the fitness curve of basic didn't change anymore, it got trapped in local. However, the fitness curve of improved GA was gradually going down, at the same time, the strength ratio curve of improved GA were keep to be greater then the threshold. It means the improved GA was able to get out of optimum and obtained a much better system layup. The improved GA offered more powerful local search ability. In the third experiment, as shown in Figure 4, both of basic GA and improved GA obtained the same result, but the improved GA converged more slowly than the basic GA. From these three experiment for single material, we knew a $[+45_6^{cr}]_s$ carbon/epoxy laminate has the least mass, and a $[+45_{11}^{gl}/+\bar{4}5^{gl}]_s$ glass laminate has the least cost. In the last experiment, the improved GA obtained a little bit better result than the basic GA, as it shown in Table 4, Compared with the $[+45_{12}^{cr}]$ laminate, the weight of a $[+45_8^{gr}/+\bar{4}5^{gl}]_s$ laminate increases 41.8%, however, the cost decreases 56%.

6. Conclusions

In this paper, a combination of CLT and improved GA are employed to minimize the weight and cost of a single-material and hybrid composite laminate, respectively, under various in-plane loading cases. Improved GA is proposed to obtain the global optimum design, results are presented in two sections, stacking sequence optimization for a single material laminate, and combined weight

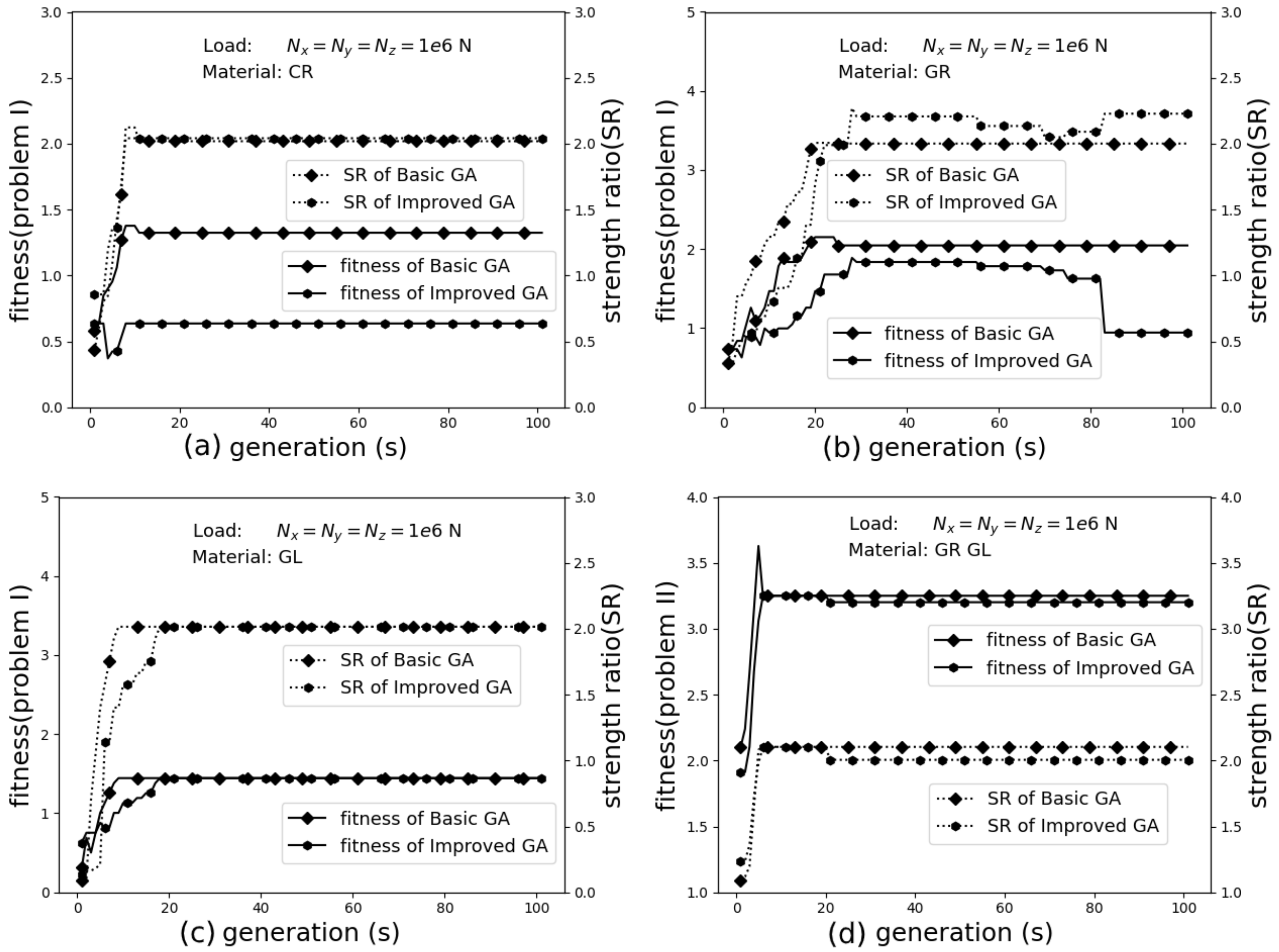

Figure 4. GA process under load $N_x = N_y = N_z$ = 1e6 N

Table 4. Optimization results

Load(N)	Problem	Algorithm	Stacking sequence	Strength ratio	Mass	Cost	Layer
$N_x = 1e6$ $N_y = 1e6$ $N_{xy} = 1e6$	I	GA	$[+45^{cr}_{11}/-45^{cr}/+\bar{4}5^{cr}]_s$	2.018	1.324	200.0	25
	I	IGA	$[+45^{cr}_{6}]_s$	2.041	0.636	96.0	12
	I	GA	$[0^{gr}_4/+45^{gr}_{12}/90^{gr}_3/+\bar{4}5]_s$	2.001	2.046	97.5	39
	I	IGA	$[+45^{gr}_9]_s$	2.227	0.945	45.0	18
	I	GA	$[+45^{gl}_{11}/+\bar{4}5^{gl}]_s$	2.015	1.444	23.0	23
	I	IGA	$[+45^{gl}_{11}/+\bar{4}5^{gl}]_s$	2.015	1.444	23.0	23
	II	GA	$[+45^{gl}/+45^{gr}_8]_s$	2.031	0.965	42.0	18
	II	IGA	$[+45^{gr}_8/+\bar{4}5^{gl}]_s$	2.005	0.902	41.0	17

and cost optimization of a carbon/epoxy, graphite/epoxy, and glass/epoxy hybrid laminate. The advantage and disadvantage of improved GA are as following:

1. During the initial phase of GA, the improved GA slows the convergence speed which increases the search cost.

2. In the second phase of GA process, the improved GA offers much more powerful local search ability, which is able to get out of local optimum.

3. Compared with the single material, the hybrid composite laminate is able to make a compromise better the weight and cost of a composite laminate.

The improved GA significantly improves the search performance, and is not easily trapped in local optima.

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References

1. Abu-Odeh AY and Jones HL (1998) Optimum design of composite plates using response surface method. *Composite structures* 43(3): 233–242.
2. Akbulut M and Sonmez FO (2008) Optimum design of composite laminates for minimum thickness. *Computers & Structures* 86(21-22): 1974–1982.
3. Choudhury A, Mondal S and Sarkar S (2019) Failure analysis of laminated composite plate under hygro-thermo mechanical load and optimisation. *International Journal of Applied Mechanics and Engineering* 24(3): 509–526.

4. Daniel IM, Ishai O, Daniel IM and Daniel I (1994) *Engineering mechanics of composite materials*, volume 3. Oxford university press New York.
5. Deka DJ, Sandeep G, Chakraborty D and Dutta A (2005) Multiobjective optimization of laminated composites using finite element method and genetic algorithm. *Journal of reinforced plastics and composites* 24(3): 273–285.
6. Fang C and Springer GS (1993) Design of composite laminates by a monte carlo method. *Journal of composite materials* 27(7): 721–753.
7. Jadhav P and Mantena PR (2007) Parametric optimization of grid-stiffened composite panels for maximizing their performance under transverse loading. *Composite structures* 77(3): 353–363.
8. Kang JH and Kim CG (2005) Minimum-weight design of compressively loaded composite plates and stiffened panels for postbuckling strength by genetic algorithm. *Composite structures* 69(2): 239–246.
9. Kim JS (2007) Development of a user-friendly expert system for composite laminate design. *Composite Structures* 79(1): 76–83.
10. Le Riche R and Haftka R (1995) Improved genetic algorithm for minimum thickness composite laminate design. *Composites Engineering* 5(2): 143–161.
11. Lin CC and Lee YJ (2004) Stacking sequence optimization of laminated composite structures using genetic algorithm with local improvement. *Composite structures* 63(3-4): 339–345.
12. Liu B, Haftka RT, Akgün MA and Todoroki A (2000) Permutation genetic algorithm for stacking sequence design of composite laminates. *Computer methods in applied mechanics and engineering* 186(2-4): 357–372.
13. Martin P (1987) Optimum design of anisotropic sandwich panels with thin faces. *Engineering optimization* 11(1-2): 3–12.
14. Massard TN (1984) Computer sizing of composite laminates for strength. *Journal of reinforced plastics and composites* 3(4): 300–345.
15. Murugan M, Suresh S, Ganguli R and Mani V (2007) Target vector optimization of composite box beam using real-coded genetic algorithm: a decomposition approach. *Structural and Multidisciplinary Optimization* 33(2): 131–146.
16. Nagendra S, Jestin D, Gürdal Z, Haftka RT and Watson LT (1996) Improved genetic algorithm for the design of stiffened composite panels. *Computers & Structures* 58(3): 543–555.
17. Naik GN, Gopalakrishnan S and Ganguli R (2008) Design optimization of composites using genetic algorithms and failure mechanism based failure criterion. *Composite Structures* 83(4): 354–367.
18. Omkar S, Khandelwal R, Yathindra S, Naik GN and Gopalakrishnan S (2008) Artificial immune system for multi-objective design optimization of composite structures. *Engineering Applications of Artificial Intelligence* 21(8): 1416–1429.
19. Park CH, Lee WI, Han WS and Vautrin A (2008) Improved genetic algorithm for multidisciplinary optimization of composite laminates. *Computers & structures* 86(19-20): 1894–1903.
20. Pelletier JL and Vel SS (2006) Multi-objective optimization of fiber reinforced composite laminates for strength, stiffness and minimal mass. *Computers & structures* 84(29-30): 2065–2080.
21. Reddy J and Pandey A (1987) A first-ply failure analysis of composite laminates. *Computers & Structures* 25(3): 371–393.
22. Riche RL and Haftka RT (1993) Optimization of laminate stacking sequence for buckling load maximization by genetic algorithm. *AIAA journal* 31(5): 951–956.
23. Sadagopan D and Pitchumani R (1998) Application of genetic algorithms to optimal tailoring of composite materials. *Composites Science and Technology* 58(3-4): 571–589.
24. Seresta O, Gürdal Z, Adams DB and Watson LT (2007) Optimal design of composite wing structures with blended laminates. *Composites Part B: Engineering* 38(4): 469–480.
25. Sivakumar K, Iyengar N and Deb K (1998) Optimum design of laminated composite plates with cutouts using a genetic algorithm. *Composite Structures* 42(3): 265–279.
26. Soares CM, Correia VF, Mateus H and Herskovits J (1995) A discrete model for the optimal design of thin composite plate-shell type structures using a two-level approach. *Composite structures* 30(2): 147–157.
27. Soeiro A, António CC and Marques AT (1994) Multilevel optimization of laminated composite structures. *Structural optimization* 7(1-2): 55–60.
28. Soremekun G, Gürdal Z, Haftka R and Watson L (2001) Composite laminate design optimization by genetic algorithm with generalized elitist selection. *Computers & structures* 79(2): 131–143.
29. Todoroki A and Haftka RT (1998) Stacking sequence optimization by a genetic algorithm with a new recessive gene like repair strategy. *Composites Part B: Engineering* 29(3): 277–285.
30. Walker M and Smith RE (2003) A technique for the multiobjective optimisation of laminated composite structures using genetic algorithms and finite element analysis. *Composite structures* 62(1): 123–128.
31. Watkins R and Morris A (1987) A multicriteria objective function optimization scheme for laminated composites for use in multilevel structural optimization schemes. *Computer Methods in Applied Mechanics and Engineering* 60(2): 233–251.
32. Zbigniew M (1996) Genetic algorithms+ data structures= evolution programs. *Computational Statistics* : 372–373.