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Laminated Composite Plate Optimization by Genetic Algorithm

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Abstract Failure analysis of laminated composite plates under different mechanical loads for different stacking sequences, fiber orientation, and composite material system is studied in this paper. An optimum composite material and laminate layup is well investigated for a targeted strength ratio which makes a compromise between weight and cost through genetic algorithm.

Keywords Genetic Algorithm · Laminates · Stacking Sequence · Hybrid Composites

1 Introduction

Composites material offer improved strength, stiffness, fatigue, and corrosion resistance, etc over conventional materials, which is widely used in automotive, aerospace, and ship building industry. 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, however, the mechanical performance of a composite material is affected by a wide range of factors, thickness, material ,and orientation of each lamina.

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, 26], weight[4, 5, 16], cost and weight[4, 15], or maximize the static strength of composite laminates for a targeted thickness[8, 9, 26]. In the present study, laminate cost and weight are minimized by modifying the objective function.

To tailor a laminate composite, genetic algorithm(GA) has been successfully applied to solve laminate design problem[2, 7, 9, 10, 13, 14, 19, 20, 22, 25, 26]. GA simulates the process of natural evolutionary includes selection, crossover, and mutation according to Darwin's principal of "survival of the fittest". Selection is the most important operator of GA which decides the diversity of the population. In this step, if the selection pressure increases, the converge speed of the population increases, however, the diversity of the population decrease. To improve the search ability and reduce the search cost, various selection

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methods have been invented, and the selection schemes 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[19, 21] and tournament[9] have been applied. The pros 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.

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 previous researchers adopted the first-ply-failure approach using the Tsai-wu failure theory [3, 5, 6, 12, 15, 17, 18, 24], Tsai-Hill[11, 23], the maximum stress[6, 15], or the maximum strain[27] static failure criteria. 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.7.

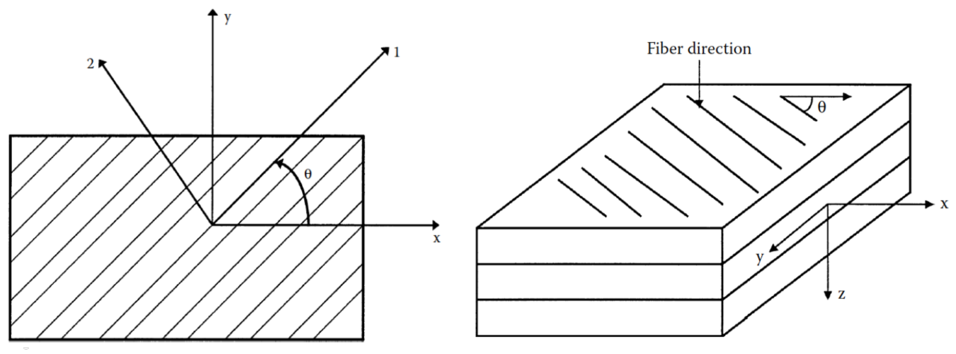

Fig. 1: Lamina

2.1 Stress and Strian in a Lamina

For a single lamina, the stress strain relation in the local axis.

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

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(in direction 1)
E_2 = transverse Young's modulus(in direction 1)
v_{12} = major Poisson's ratio
G_{12} = in-plane shear modulus (in plane 1-2)

Stress strain relation in global axis are

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

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 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

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

where

$$
\begin{aligned}
A_{ij} &= \sum_{k=1}^{n} (\overline{Q_{ij}})_k (h_k - h_{k-1}) \\
B_{ij} &= \frac{1}{2} \sum_{k=1}^{n} (\overline{Q_{ij}})_k (h_k - h_{k-1}) \\
D_{ij} &= \frac{1}{3} \sum_{k=1}^{n} (\overline{Q_{ij}})_k (h_k - h_{k-1})
\end{aligned}
\tag{8}
$$

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

3 Failure Theories of an Angle Lamina

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(in direction 1),
$(\sigma_1^C)_{ult}$ = Ultimate longitudinal compressive strength(in direction 1),
$(\sigma_2^T)_{ult}$ = Ultimate transverse tensile strength(in direction 2),
$(\sigma_2^C)_{ult}$ = Ultimate transverse compressive strength(in direction 2), 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

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 laminated composites

4.1 Genetic Algorithm

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.

GA employs various selection strategies to diversity the population and prevent the population from premature . Parents are selected by three various approaches, the first method is according to individual's fitness, individuals with higher fitness are more inclined to be chosen, the second way is sort the population according to the absolute difference of individual's strength ratio and specified safety factor in an incresing order, individual with smaller difference are more likely to be selected; the third method is select individuals which satisfy the safty factor constraint, individual with best fitness are more likely be selected. Individuals seleced from these three approaches form 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 4). 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 4) and parent 2(as shown in Figure 3) 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].

+45	-45	-45	0	-45	-45	+45	0	1	1	2	1	1	0
Orientation Gene							Material Gene						

Fig. 2: Parent 1

+45	+45	-45	-45	-45	-45	+45	+45	1	0	0	1	1	0	0	1

Fig. 3: Parent 2

+45	-45	-45	0	-45	-45	+45

P_{1o}

0	1	1	2	1	1	0

P_{1m}

+45	+45	-45	-45	-45	-45	+45	+45

$P2_o$

1	0	0	1	1	0	0	1

$P2_m$

+45	-45	-45	-45	-45	-45	-45	+45

$P1_o$ $P2_o$

0	1	0	1	1	0	1	0

$P1_m$ $P2_m$

Fig. 4: Crossover Operation

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 5

+45	-45	-45	-45	-45	-45	-45	+45	0	1	0	1	1	0	1	0

Orientation Mutation Material Mutation

0	-45	-45	-45	-45	-45	-45	0	0	0	0	1	1	0	0	0

Fig. 5: Mutation

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:

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

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 $1000 \times 1000 \times 0.165 mm^3$ 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.

Table 1: GA parameters

Parameter	Population size	Encoding	Crossover Strategy	Mutation strategy
Value	10	Integer	One-point	Mass mutation

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

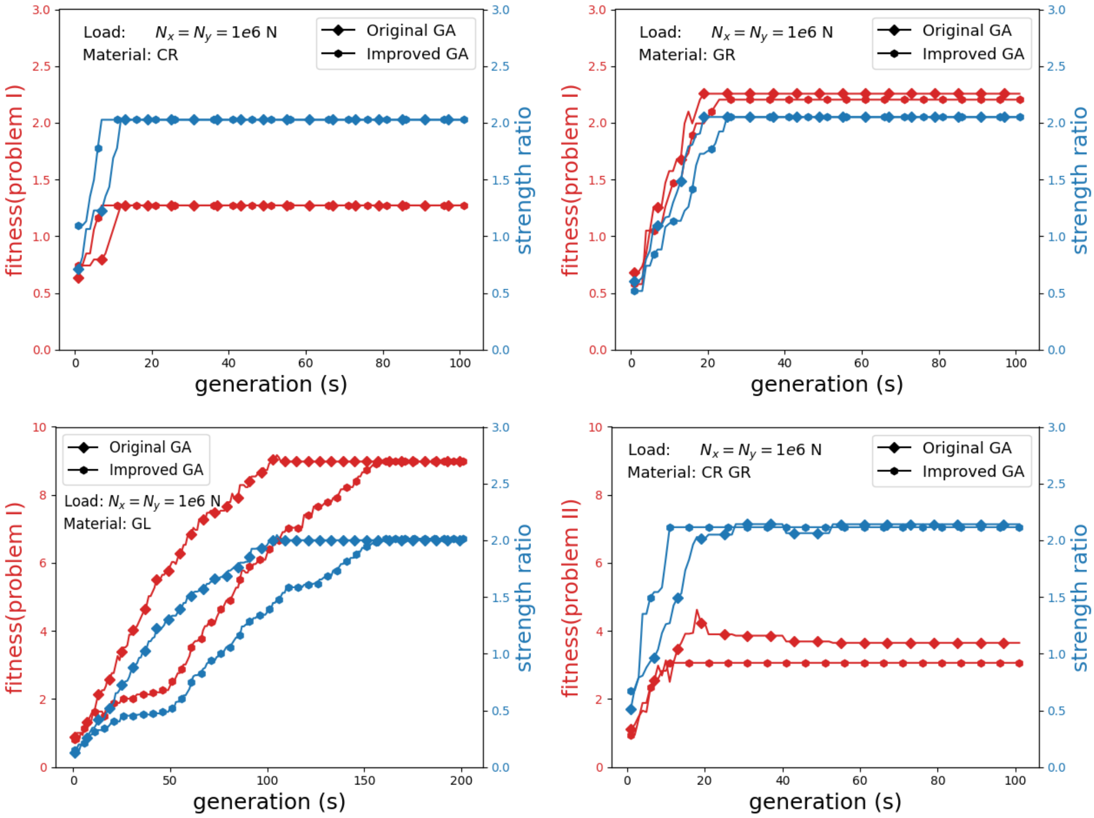

Fig. 6: GA process for $N_x = N_y$ = 1e6 N

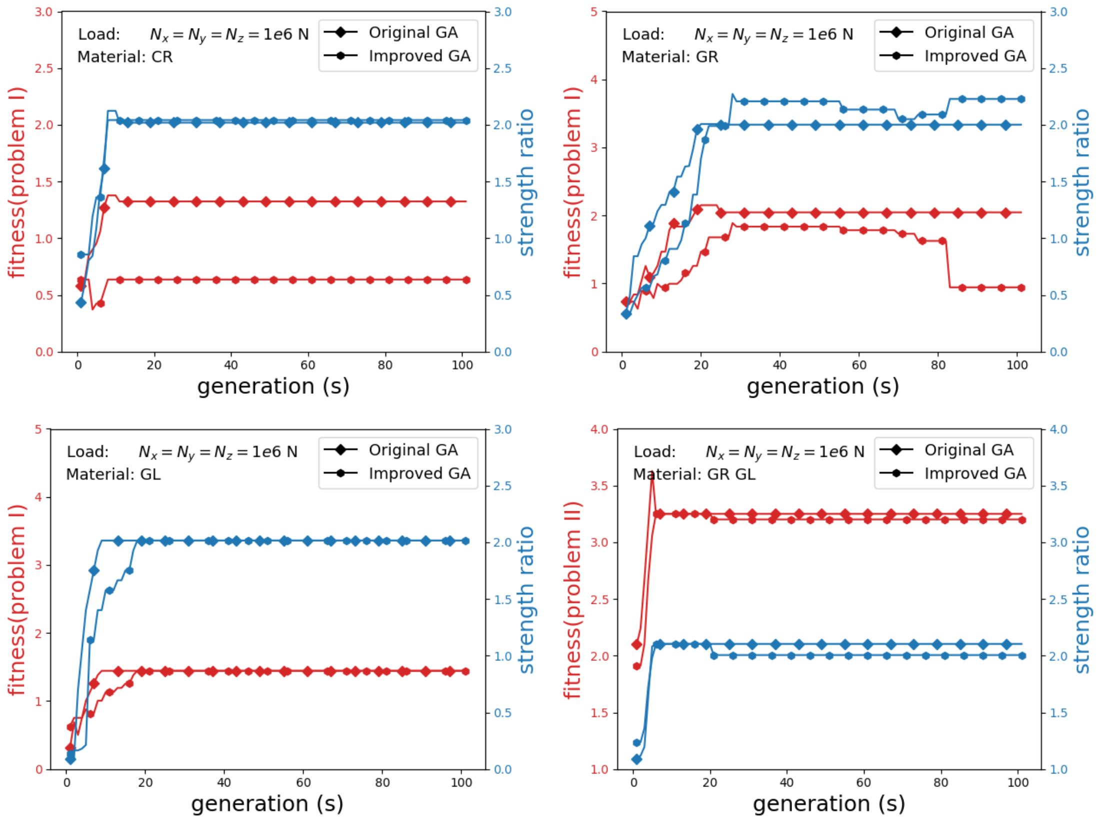

Fig. 7: GA process for $N_x = N_y = N_{xy} = 1e6$ N

In the present experiment, the optimum composite system, layup, thickness, and number of layers for a targeted strength ratio(2 in this paper) under various in-plane loading is investigated.

Table 3: Optimization results

Load(N)	Problem	Algorithm	Stacking sequence	Strength ratio	Mass	Cost	Layer
	I	GA	$[-45_6^{cr}/+45_6^{cr}]_s$	2.026	1.271	192.0	24
	I	IGA	$[-45_6^{cr}/+45_6^{cr}]_s$	2.026	1.271	192.0	24
$N_x = 1e6$	I	GA	$[0_6^{gr}/-45_4^{gr}/+45_4^{gr}/90_7^{gr}/9\bar{0}^{gr}]_s$	2.051	2.256	107.5	43
$N_y = 1e6$	I	IGA	$[+45_{10}^{gr}/-45_{21}^{gr}/+45_{10}^{gr}]$	2.024	2.151	102.5	41
	I	GA	$[-45_{35}^{gl}/+45_{73}^{gl}/+45_{35}^{gl}]$	2.001	8.980	143.0	143
	I	IGA	$[-45_{35}^{gl}/+45_{73}^{gl}/+45_{35}^{gl}]$	2.001	8.980	143.0	143
	II	GA	$[-45_{12}^{gr}/+45_5^{cr}/+45_7^{gr}]_s$	2.141	2.523	175	48
	II	IGA	$[-45_9^{gr}/+45_9^{gr}/-45_2^{cr}/+45_2^{cr}]_s$	2.054	2.313	154	44
	I	GA	$[+45_{11}^{cr}/-45^{cr}/+\bar{4}5^{cr}]_s$	2.018	1.324	200.0	25
$N_x = 1e6$	I	IGA	$[+45_{12}^{cr}]$	2.041	0.636	96.0	12
$N_y = 1e6$	I	GA	$[0_4^{gr}/+45_{12}^{gr}/90_3^{gr}/+\bar{4}5]_s$	2.001	2.046	97.5	39
$N_{xy} = 1e6$	I	IGA	$[+45_{18}^{gr}]$	2.227	0.945	45.0	18
	I	GA	$[+45_{23}^{gl}]$	2.015	1.444	23.0	23
	I	IGA	$[+45_{23}^{gl}]$	2.015	1.444	23.0	23
	II	GA	$[+45^{gl}/+45_{16}^{gr}/+45^{gl}]$	2.031	0.965	42.0	18
	II	IGA	$[+45_8^{gr}/+\bar{4}5^{gl}]_s$	2.005	0.902	41.0	17

Subscript ”cr” denotes a carbon/epoxy ply, ”gr” denotes graphite/epoxy ply, ”gl” denotes a glass/epoxy ply

6 Conclusions

In this paper, a combination of CLT and GA is employed to minimize the weight and cost of a single-material and hybrid composite laminate, respectively, under various in-plane loading cases. 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 and cost optimization of a carbon/epoxy, graphite/epoxy, and glass/epoxy hybrid laminate.

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References

1. Akram Y Abu-Odeh and Harry L Jones. Optimum design of composite plates using response surface method. *Composite structures*, 43(3):233–242, 1998.
2. Mustafa Akbulut and Fazil O Sonmez. Optimum design of composite laminates for minimum thickness. *Computers & Structures*, 86(21-22):1974–1982, 2008.
3. A Choudhury, SC Mondal, and S Sarkar. Failure analysis of laminated composite plate under hygro-thermo mechanical load and optimisation. *International Journal of Applied Mechanics and Engineering*, 24(3):509–526, 2019.
4. Dhyan Jyoti Deka, G Sandeep, D Chakraborty, and A Dutta. Multiobjective optimization of laminated composites using finite element method and genetic algorithm. *Journal of reinforced plastics and composites*, 24(3):273–285, 2005.
5. Chin Fang and George S Springer. Design of composite laminates by a monte carlo method. *Journal of composite materials*, 27(7):721–753, 1993.

6. Prakash Jadhav and P Raju Mantena. Parametric optimization of grid-stiffened composite panels for maximizing their performance under transverse loading. *Composite structures*, 77(3):353–363, 2007.
7. Ji-Ho Kang and Chun-Gon Kim. Minimum-weight design of compressively loaded composite plates and stiffened panels for postbuckling strength by genetic algorithm. *Composite structures*, 69(2):239–246, 2005.
8. Jung-Seok Kim. Development of a user-friendly expert system for composite laminate design. *Composite Structures*, 79(1):76–83, 2007.
9. Ching-Chieh Lin and Ya-Jung Lee. Stacking sequence optimization of laminated composite structures using genetic algorithm with local improvement. *Composite structures*, 63(3-4):339–345, 2004.
10. Boyang Liu, Raphael T Haftka, Mehmet A Akgün, and Akira Todoroki. Permutation genetic algorithm for stacking sequence design of composite laminates. *Computer methods in applied mechanics and engineering*, 186(2-4):357–372, 2000.
11. PMJW Martin. Optimum design of anisotropic sandwich panels with thin faces. *Engineering optimization*, 11(1-2):3–12, 1987.
12. Thierry N Massard. Computer sizing of composite laminates for strength. *Journal of reinforced plastics and composites*, 3(4):300–345, 1984.
13. MS Murugan, S Suresh, R Ganguli, and V Mani. Target vector optimization of composite box beam using real-coded genetic algorithm: a decomposition approach. *Structural and Multidisciplinary Optimization*, 33(2):131–146, 2007.
14. Somanath Nagendra, D Jestin, Zafer Gürdal, Raphael T Haftka, and Layne T Watson. Improved genetic algorithm for the design of stiffened composite panels. *Computers & Structures*, 58(3):543–555, 1996.
15. SN Omkar, Rahul Khandelwal, Santhosh Yathindra, G Narayana Naik, and S Gopalakrishnan. Artificial immune system for multi-objective design optimization of composite structures. *Engineering Applications of Artificial Intelligence*, 21(8):1416–1429, 2008.
16. Chung Hae Park, Woo Il Lee, Woo Suck Han, and Alain Vautrin. Improved genetic algorithm for multidisciplinary optimization of composite laminates. *Computers & structures*, 86(19-20):1894–1903, 2008.
17. Jacob L Pelletier and Senthil S Vel. Multi-objective optimization of fiber reinforced composite laminates for strength, stiffness and minimal mass. *Computers & structures*, 84(29-30):2065–2080, 2006.
18. JN Reddy and AK Pandey. A first-ply failure analysis of composite laminates. *Computers & Structures*, 25(3):371–393, 1987.
19. Rodolphe Le Riche and Raphael T Haftka. Optimization of laminate stacking sequence for buckling load maximization by genetic algorithm. *AIAA journal*, 31(5):951–956, 1993.
20. D Sadagopan and R Pitchumani. Application of genetic algorithms to optimal tailoring of composite materials. *Composites Science and Technology*, 58(3-4):571–589, 1998.
21. Omprakash Seresta, Zafer Gürdal, David B Adams, and Layne T Watson. Optimal design of composite wing structures with blended laminates. *Composites Part B: Engineering*, 38(4):469–480, 2007.
22. K Sivakumar, NGR Iyengar, and Kalyanmoy Deb. Optimum design of laminated composite plates with cutouts using a genetic algorithm. *Composite Structures*, 42(3):265–279, 1998.
23. CM Mota Soares, V Franco Correia, H Mateus, and J Herskovits. 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, 1995.
24. AV Soeiro, CA Conceição António, and A Torres Marques. Multilevel optimization of laminated composite structures. *Structural optimization*, 7(1-2):55–60, 1994.
25. Akira Todoroki and Raphael T Haftka. Stacking sequence optimization by a genetic algorithm with a new recessive gene like repair strategy. *Composites Part B: Engineering*, 29(3):277–285, 1998.

26. Mark Walker and Ryan E Smith. A technique for the multiobjective optimisation of laminated composite structures using genetic algorithms and finite element analysis. *Composite structures*, 62(1):123–128, 2003.
27. RI Watkins and AJ Morris. 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, 1987.