JAST, Vol. 12, No. 1, pp. 27-36

JAST Journal of Aerospace Science and Technology

Multi-objective Optimization of Buckling Load for a Laminated Composite Plate by Coupling Genetic Algorithm and FEM

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In this paper, a mixed method has been developed by coupling Multi-Objective Genetic Algorithms (MOGA) and Finite Element Method (FEM). This method has been applied for determination of the optimal stacking sequence of laminated composite plate against buckling. The most important parameters in optimization of a laminated composite plate, e.g. angle, thickness, number, and material of each layer are considered in the proposed method. These optimization processes have been done for 3 types of compressive loads and optimal stacking sequences and Pareto front for each kind of compressive loads are determined. Unlike estimation methods like response surface and simple analytic methods, in the proposed optimization algorithm, objective functions are calculated directly by FEM software which leads to precise results. The results of the proposed algorithm are validated with the existing data in literature. The effects of different boundary conditions and aspect ratio of plate on Pareto front in buckling of a laminated composite plate are also studied.

Keywords: Laminated composite plates, Buckling load, Multi-Objective Genetic Algorithm (MOGA), Finite element method (FEM), Pareto front

Introduction

Recently, utilizing laminated composite plates has been increased in various industries due to their mechanical specifications. Buckling is a very important failure mode in laminated composite plates. The critical buckling load in these structures depends on different parameters including, angle, thickness, number, material of each layer and boundary conditions of the plate [1-10]. Therefore, optimizations of stacking sequence in composite plates becomes essential for using these structures. Among several algorithms for optimization, Genetic Algorithms (GAs) have been widely used for optimization of stacking sequence in composite materials [11-18]. Various objectives could be considered in stacking sequence optimization including weight, natural frequencies, cost, and buckling load. Over the past few years, stacking sequence optimization in composite materials has been focused on optimizing weight and structural strength. In this regards, Schmit and Farshi [19] studied optimum design for composite laminates by consideration of strength and stiffness. Soremekun et al. [20] utilized genetic algorithms for stacking sequence optimization of composite structures. Chakraborty and Dutta [21] optimized Fiber Reinforced Polymer (FRP) composites against impact induced failure by utilizing island model parallel genetic algorithm. Lay-up optimization of composite pressure vessel utilizing FEM to achieve minimum weight has been studied by Mian et al. [22]. Todoroki and Ishikawa [23] optimized stacking sequence of composite laminates utilizing genetic algorithm and response surface method. Falzon and Faggiani [24] studied the post buckling behavior of composite structures using genetic algorithm.

Regarding the presented literature review, a few researches have coupled multi-objective genetic algorithm and FEM for optimization of buckling load and weight of composite plates simultaneously. Also, consideration of all the most important parameters in optimization of a laminated composite plate such as angle, thickness, number, and material of each layer has not been attended, yet. In this paper, a coupled Multi-Objective Genetic Algorithm (MOGA) and FEM is proposed for determination of optimal stacking sequence for a composite plate under three types of compressive loading by considering all the most important parameters in optimization of a laminated composite plate. In this research, the minimized weight and the maximized buckling load of the composite plate are considered as objective functions. The effects of different boundary conditions and aspect ratio of plate on Pareto front in the buckling of a laminated composite plate are also studied.

Buckling of a Rectangular Composite Plate Compressed in twoPerpendicular Directions

A rectangular composite plate with simply support edges under uniformly distributed compressive forces of nF and F is illustrated in Fig. 1.

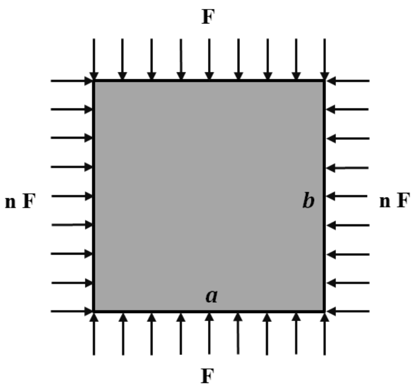

Fig. 1. Rectangular composite plate compressed in two perpendicular directions

In the symmetric laminated plate shown, the bending-extension coupling stiffness matrix is zero $\left(B=[0]\right)$. Thus, the strain energy stored in the plate could be written as [25]:

$$U=\frac{1}{2}\int_0^a\int_0^b\left[\begin{array}{l}D_{11}\left(\frac{\partial^2 w_0}{\partial x^2}\right)^2+D_{22}\left(\frac{\partial^2 w_0}{\partial y^2}\right)^2+D_{66}\left(\frac{2\partial^2 w_0}{\partial x\partial y}\right)^2\\+2\left(D_{12}\frac{\partial^2 w_0}{\partial x^2}\frac{\partial^2 w_0}{\partial y^2}+D_{16}\frac{\partial^2 w_0}{\partial x^2}\frac{2\partial^2 w_0}{\partial x\partial y}+D_{26}\frac{\partial^2 w_0}{\partial y^2}\frac{2\partial^2 w_0}{\partial x\partial y}\right)\end{array}\right]dydx \quad (1)$$

Where, D_{ij} and w_o are components of bending stiffness matrix and out of plate displacement, respectively. Also, *a* and *b* are dimensions of plate along x and y direction, respectively. If only constant in plane forces is applied to the plate, work of external forces could be written as follows:

$$\Omega=\frac{1}{2}\int_0^a\int_0^b\left[N_x\left(\frac{\partial w_0}{\partial x}\right)^2+N_y\left(\frac{\partial w_0}{\partial y}\right)^2\right]dydx \quad (2)$$

In which:

$$\begin{aligned}N_x&=-\lambda nF\\N_y&=-\lambda F\end{aligned} \quad (3)$$

Where, N_x and N_y are in plane forces along x and y direction, respectively. λ is eigenvalue of buckling. The deflection surface of the buckled plate can be demonstrated, in the case of simply support edges, by the double series as [26]:

$$w_0=\sum_{i=1}^{\infty}\sum_{j=1}^{\infty}w_{ij}\sin\frac{i\pi x}{a}\sin\frac{j\pi y}{b} \quad (4)$$

w_{ij} is constant and could be calculated from the conservation of energy law (see Eq. 5).

$$\frac{\partial\pi_p}{\partial w_{ij}}=\frac{\partial\left(U+\Omega\right)}{\partial w_{ij}} \quad (5)$$

Where, U and Ω are stored strain energy and work of external forces, respectively. By substituting w_0 from Eq. (4) in Eqs. (1) and (2) and using Eq. (5), buckling eigenvalues for an orthotropic plate with $D_{16}=D_{26}=0$ could be written as:

$$\left(\lambda_{cr}\right)_{ij}=\frac{\pi^2\left[D_{11}\left(\frac{i}{a}\right)^4+2\left(D_{12}+2D_{66}\right)\left(\frac{i}{a}\right)^2\left(\frac{j}{b}\right)^2+D_{22}\left(\frac{j}{b}\right)^4\right]}{nF\left(\frac{i}{a}\right)^2+F\left(\frac{j}{b}\right)^2} \quad (6)$$

Minimum value of Eq. (6) for $i,j=1,2,3,\ldots$ is the first buckling eigenvalue.

Description of the EmployedOptimization Algorithm

Genetic algorithm (GA) is a common way of finding optimal solution in difficult problems. GA uses four elements [27, 28]: cross-over, mutation, a stopping criterion and selection. Crossover is a reproduction method that mixes genes of two chromosomes to produce new chromosomes and is used in three forms which are shown in Fig. 2.

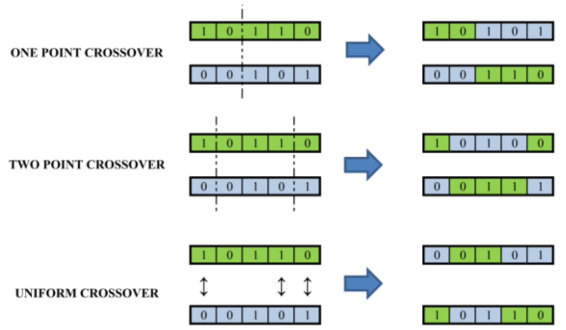

Fig. 2. Typical forms of crossover operator in genetic algorithm

Mutation slightly modified some genes of selected chromosomes to cover diversity among the population for finding global optimum of the function [29]. The application of GA also needs the generation of a population of candidate solutions as a starting point which evolves iteratively new, gradually better populations from the previous ones until the stopping criterion is satisfied. There are several stopping criteria that have been checked at this step and the optimization process will converge if one of them is satisfied; otherwise, the algorithm will start from evaluation new genes.

In this study, Multi-Objective Genetic Algorithm (MOGA) and Finite Element Method (FEM) are coupled to obtain the optimum solutions of defined objective functions. This method is modification of previous algorithm that has been presented by authors for multi objective optimization [30]. In this method, objective functions were directly recalculated by FEM in each evaluation. At the end of the process, MOGA creates new individuals which are new lamination parameters for stacking sequence including number of layers, thickness, material and angle of each layer. Afterwards, these parameters are transferred to FEM software. In FEM software, geometric modeling, meshing and applying loads, and boundary conditions are generated automatically and the results obtained by FEM software including buckling load and weight are retransferred to the MOGA process. This process will continue until the convergence criterion is satisfied. Fig. 3 illustrates the flowchart of the proposed method for multi objective optimization of composite structures. Unlike estimation methods like response surface, in the proposed optimization algorithm, objective functions are calculated directly by FEM software which generates precise results.

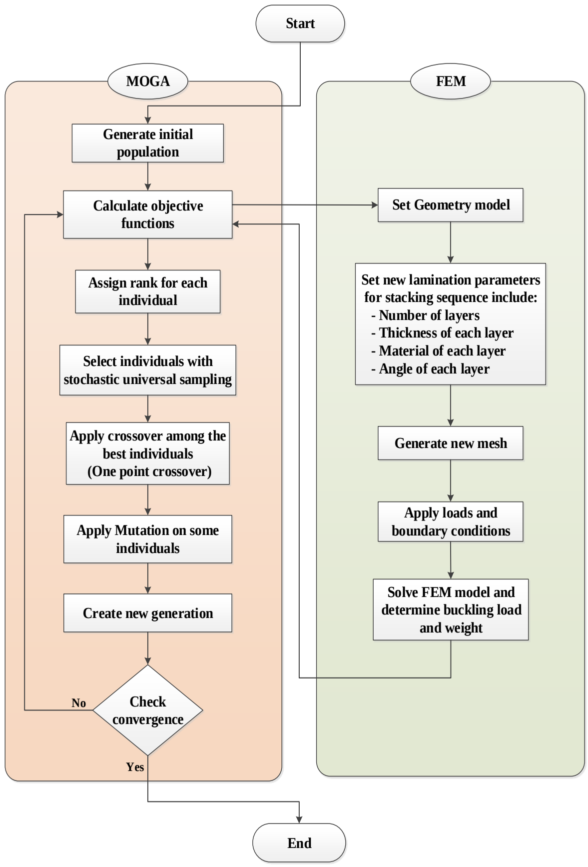

Fig. 3. Flowchart of the proposed method for multi-objective optimization of composite structures

The goals of optimization are to maximize the laminated composite plate buckling load and minimize its weight simultaneously. The design independent variables for optimization are: number of layers, thickness, material properties and fiber angle of each layer. Allowable bounds of each parameter are presented in Table 1. Also, utilized materials are listed in Table 1 and their mechanical properties in Table 2. The MOGA parameters for optimization are initial population of 100, elitist choice of 3%, Mutation probability of 2%, crossover probability of 50%, and convergence Pareto percentage of 99%.

Table. 1. Allowable bounds of parameters in optimization

Parameter	Lower bound	Upper bound	Step	Number of possible variables
Number of layers	1	10	1	10
Thickness of layers	0.5 mm	2 mm	0.125 mm	13
Material	-	-	-	3
Angle of layers	-90 deg.	+90 deg.	5 deg.	36

Finite Element Modeling of Laminated Composite Plate Compressed in two Perpendicular Directions

As described in the section 3, in the proposed algorithm, objective functions (i.e. buckling load and weight) are calculated in FEM software. In this regards, several three dimensional finite element models of laminated composite plate compressed in two perpendicular directions were modeled automatically in the ABAQUS software. The dimensions of laminated composite plate are $a=b=1^{m}$. For determination of optimal number of elements in finite element modeling, mesh sensitivity analyses should be performed. In this regards, critical buckling load of carbon composite plate with layout $\left[90_{10}\right]$ for 3 different types of compressive loads which are defined by n=0, 1 and 2 versus number of elements have been illustrated in Fig. 4. According to this figure, after about 5000 elements, the numerical results have converged. Therefore, the optimum number of elements in the numerical modeling is 5041.

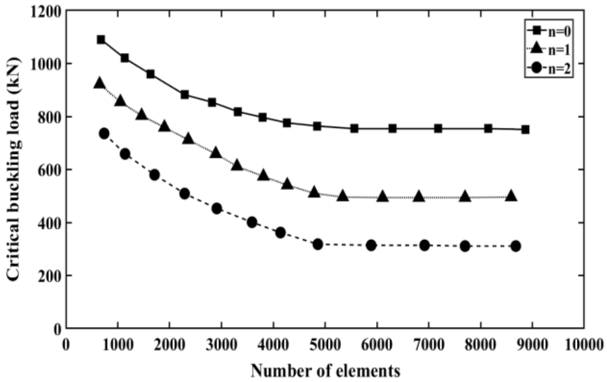

Fig. 4. Critical buckling load of carbon composite plate with layout $\left[90_{10}\right]$ for 3 different types of compressive loads versus number of elements

Mesh pattern and ply stacking sequence for a composite plate with layout $\left[-60/90/60/-60/-75/90/75\right]$ are shown in Fig. 5. As mentioned in the previous section, three kinds of material, i.e. Carbon/Epoxy, Glass/Epoxy and Kevlar/Epoxy, are considered as the material of each layer in the ABAQUS code. The mechanical properties of materials used in the ABAQUS code are listed in Table 2.

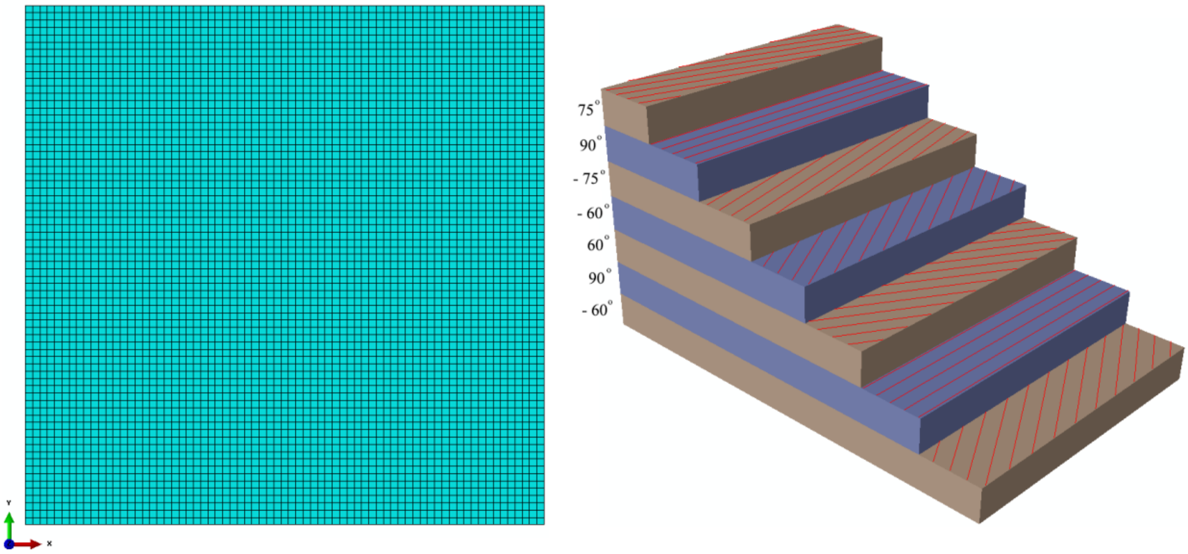

Fig. 5. Mesh pattern and ply stacking sequence for a composite plate with layout $\left[-60/90/60/-60/-75/90/75\right]$

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Table. 2. The mechanical properties of used materials in the ABAQUS code

Material	E_1 (GPa)	E_2 (GPa)	υ_{12}	G_{12} (GPa)	ρ (kg)
Carbon/Epoxy (C/E)	121	8.6	0.27	4.7	1490
Glass/Epoxy (G/E)	45	10	0.3	5	2000
Kevlar/Epoxy (K/E)	80	5.5	0.34	2.2	1400

The first three buckling mode shapes of composite plate with layout $[90_{10}]$ for 3 different types of compressive loads which are defined by n=0, 1 and 2 with the simply support boundary condition in all edges are illustrated in Fig. 6. As shown in Fig. 1, n=0 corresponds to uniaxial buckling and n=1 and 2 correspond to biaxial buckling. According to Fig. 6, it is revealed that, regardless of the type of compressive loads, first mode shape of buckling is the same for the composite plate with the simply support boundary condition in all edges.

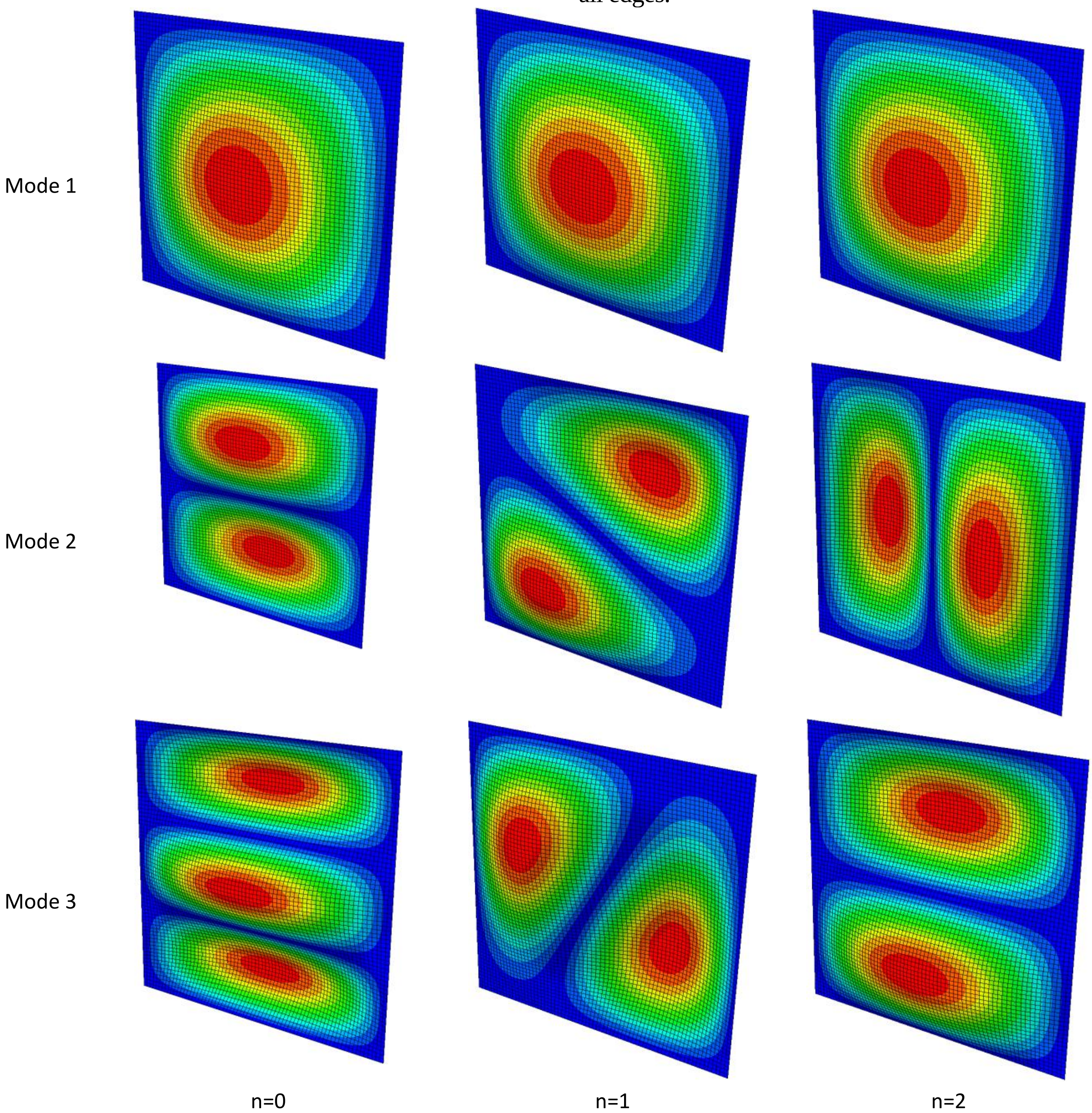

Fig. 6. The first three buckling mode shapes of composite plate with layout $[90_{10}]$ for 3 different types of compressive loads with the simply support boundary condition in all edges and a/b=1

Results and discussion

The proposed algorithms presented in this paper were employed to perform the optimization of stacking sequence for a laminated composite plate which is shown in Fig. 1. The dimensions of laminated composite plate were considered as $a=b=1^m$ and the boundary condition in all edges was considered as simply support. The optimization was done for 3 types of compressive loads which are defined by n=0, 1 and 2. The buckling load versus weight which is calculated in optimization process for 3 different types of compressive loads was depicted in Figs. 7 to 9. The figures show that the design space could be searched through optimization process. As it could be found, the optimal points divide the space into two feasible and infeasible parts. That means in a certain weight, there is no possibility to obtain a higher buckling load than the one that was found in the optimal points.

By the selection of the optimal point located on the upper boundary, Pareto front for 3 different types of compressive loads can be obtained. A graphic representation of Pareto front for 3 different types of compressive loads with the simply support boundary condition in all edges and a/b=1 was elaborated and is shown in Fig. 10. Based on this figure, it is shown that the buckling load increases with the increase of n. Therefore, maximum buckling resistance is reached when n=0, and minimum buckling resistance happens when n=2, in certain weight and similar conditions. Also, by investigating Pareto front some extra decisions could be obtained. The first decision is obtained by considering the lowest point in Pareto front. In this point, the lowest values of buckling load and weight are obtained. The lamination parameters for stacking sequence that correspond to this point, are appropriate in some applications that weight is the most important goal. In these applications, buckling load is not an important target. On the other extreme of the Pareto front, the highest value of buckling load is reached. Also, the highest value of weight is obtained in this point too. The lamination parameters for stacking sequence that correspond to this point, are appropriate in some applications in which resistance to buckling is the most important aim. In these applications, weight is not an important goal. All the other points in Pareto front are intermediate cases. These points could be utilized when a certain buckling load and weight is needed. Therefore, Pareto front graph helps the designer to make a good decision by regarding all design's criteria. The lamination parameters for stacking sequence include number, thickness, material properties and angle of each layer in some of the Pareto front points in 3 types of compressive loads with the simply support boundary condition in all edges and a/b=1 are presented in Table 3, (p. 37).

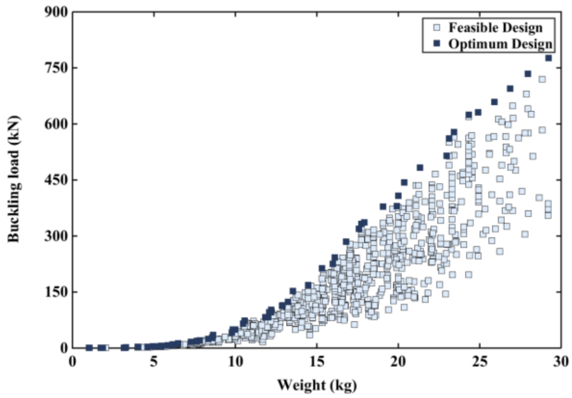

Fig. 7. The buckling load vs. weight for n=0 and a/b=1 with the simply support boundary condition

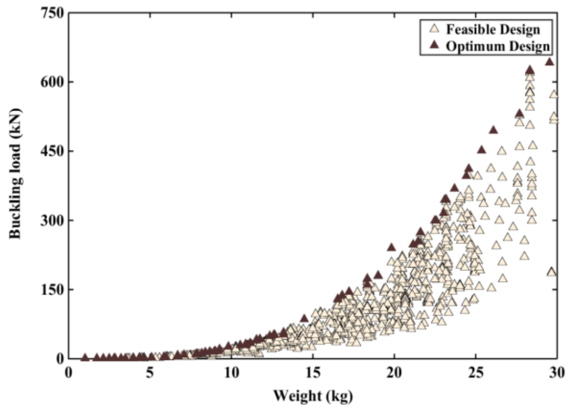

Fig. 8. The buckling load vs. weight for n=1 and a/b=1 with the simply support boundary condition

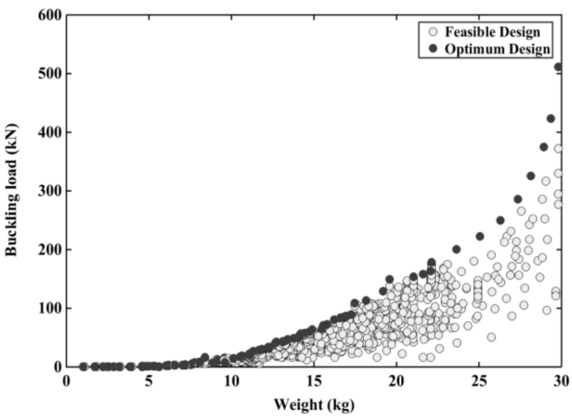

Fig. 9. The buckling load vs. weight for n=2 and a/b=1 with the simply support boundary condition

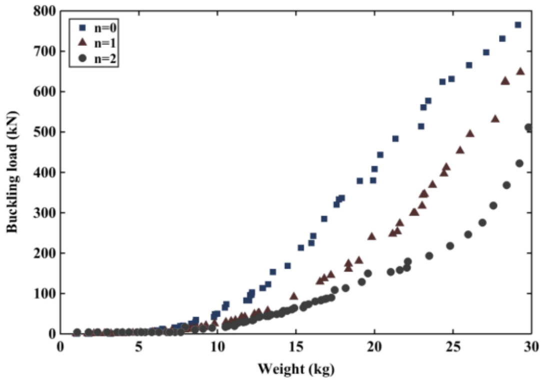

Fig. 10. Comparison of Pareto front for 3 different types of compressive loads with the simply support boundary condition in all edges and $a/b=1$

Convergence Pareto percentage versus number of generations for 3 different types of compressive loads are shown in Fig. 11. As it can be seen, MOGA has converged after 13th, 12th and 14th generation for $n=0$, 1 and 2, respectively. This is due to the fact that the difference between types of compressive loads leads to different search paths to be taken by MOGA to converge to the optimal solution.

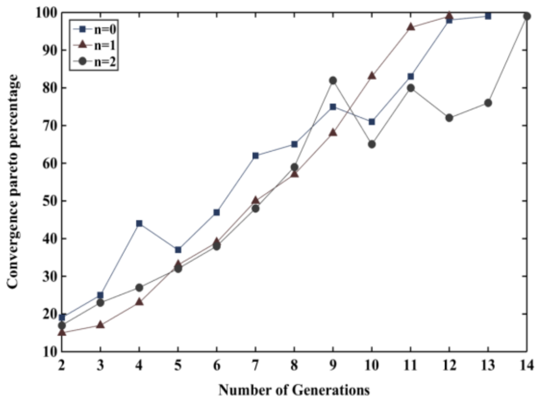

Fig. 11. Convergence Pareto percentage versus number of generations for 3 different types of compressive loads with the simply support boundary condition in all edges and $a/b=1$

Effects of Different Boundary Conditions on Pareto Front

In this section, effects of different boundary conditions on Pareto front in buckling of a rectangular laminated composite plate have been investigated. In this regards, three different kinds of boundary conditions including Simply support (S), Free (F) and Clamp (C) have been considered. Three case studies with different kinds of boundary conditions in each edge for investigation of these effects have been chosen. In the all chosen case studies, laminated composite plates have been modeled with dimensions of $a=b=1^{m}$. Also, loading condition in all of the chosen case studies has been considered as biaxial with $n=1$. The buckling load versus weight for the three case studies mentioned, with different kinds of boundary conditions in each edge with $n=1$ and $a/b=1$, are illustrated in Figs. 12 to 14. It is obvious from the results that the highest buckling load occurs when S-C-S-C boundary conditions are employed.

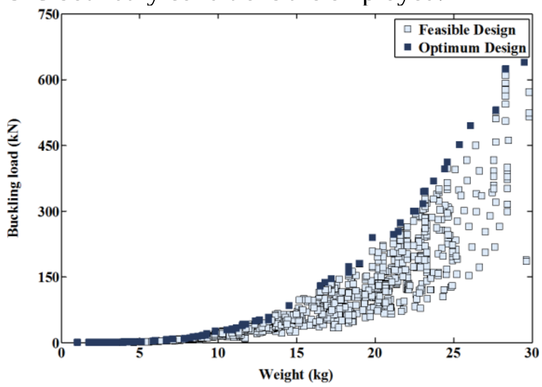

Fig. 12. The buckling load vs. weight for the composite plate with S-S-S-S boundary conditions at $n=1$ and $a/b=1$

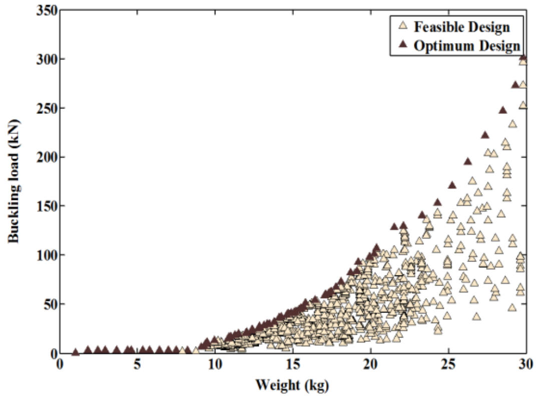

Fig. 13. The buckling load vs. weight for the composite plate with S-F-S-F boundary conditions at $n=1$ and $a/b=1$

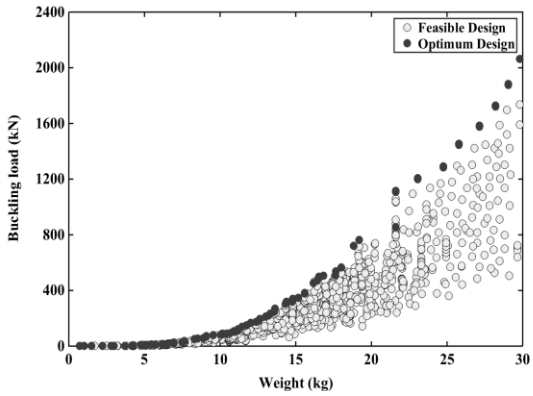

Fig. 14. The buckling load vs. weight for the composite plate with S-C-S-C boundary conditions at $n=1$ and $a/b=1$

Comparison of Pareto front for 3 different kinds of boundary conditions in each edge with n=1 and a/b=1 are shown in Fig. 15. It is seen that the buckling load increases exponentially when boundary condition is changed from free to clamp. Also, it is found that slope of the curve increases dramatically when boundary condition is changed to clamp. Therefore, boundary conditions have an important effect on Pareto front in buckling of composite plate.

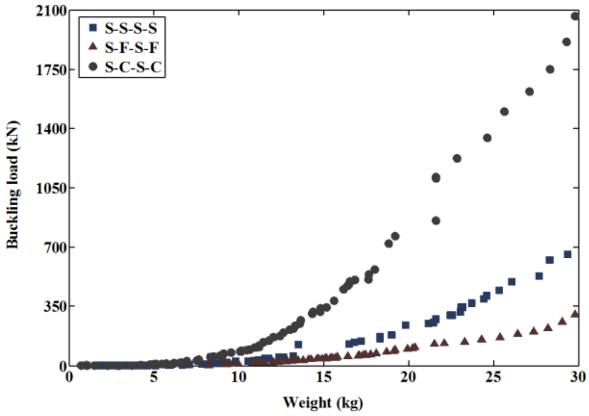

Fig. 15. Comparison of Pareto front for 3 different kinds of boundary conditions in each edge with n=1 and a/b=1

Effects of different aspect ratios of plate on Pareto front

In this section, effects of different aspect ratios of plate on Pareto front in buckling of a rectangular laminated composite plate have been studied. In this regards, three different aspect ratios of plate including a/b=1, 1.5 and 2 have been considered. Three case studies with different aspect ratios for investigation of these effects have been chosen. In the all of the chosen case studies, boundary conditions in all edges have been modeled as simply support. Also, loading condition in all of the chosen case studies has been considered as biaxial with n=1. For reaming weight constant in different aspect ratios, width of plate (a) and height of plate (b) were considered as a=b=1^{m}, a=1.225^{m}; b=0.816^{m} and a=1.414^{m}; b=0.707^{m} for a/b=1,1.5 and 2, respectively. The buckling load versus weight for the three case studies mentioned with different aspect ratios of plate with the simply support boundary condition in all edges and n=1 are shown in Figs. 16 to 18. It is obvious from the results that the highest buckling load occurs when aspect ratio of plate is 1.

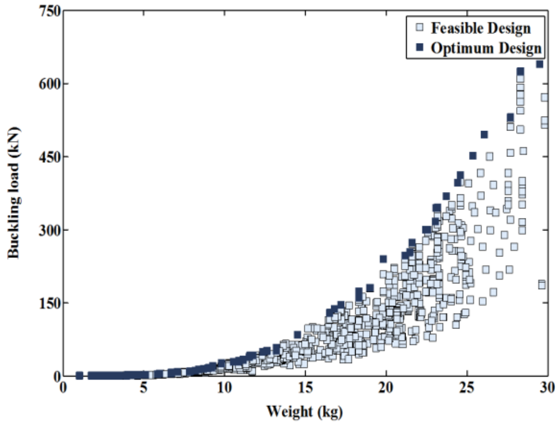

Fig. 16. The buckling load vs. weight for the aspect ratio a/b=1 with the simply support boundary condition in all edges and n=1

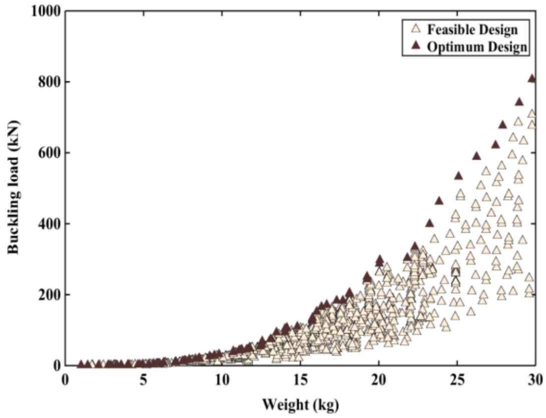

Fig. 17. The buckling load vs. weight for the aspect ratio a/b=1.5 with the simply support boundary condition in all edges and n=1

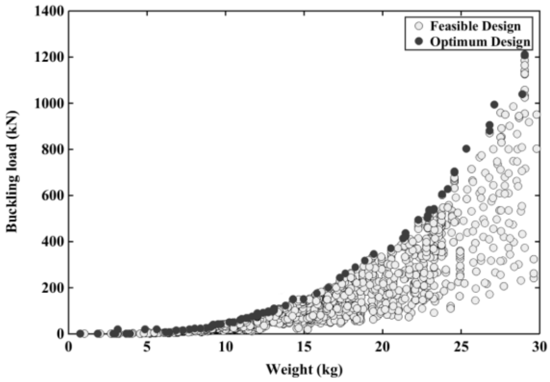

Fig. 18. The buckling load vs. weight for the aspect ratio a/b=2 with the simply support boundary condition in all edges and n=1

Comparison of Pareto front for 3 different aspect ratios of plate with the simply support boundary condition in all edges and n=1 are illustrated in Fig. 19. It may be noticed from Fig. 19 that, the buckling load increases with the increase of a/b ratio. The reason for this is that increase in the aspect ratio of plate tends to decrease the effective length of laminated composite plate and consequently, increases the buckling load.

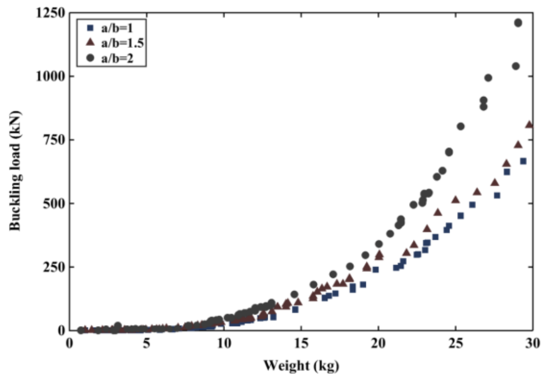

Fig. 19. Comparison of Pareto front for 3 different aspect ratios of plate with the simply support boundary condition in all edges and n=1

Verification of the proposed algorithm

To verify the proposed algorithm which was described in the previous section, the obtained Pareto front by the proposed algorithm is compared with those presented by Shi et al. [31]. They employed a hybrid genetic algorithm for optimal design of the advanced grid-stiffened (AGS) carbon-fiber triangular grid conical shells under external pressure. Comparison of the results between the proposed algorithm, and Ref. [31] is shown in Fig. 20. The obtained Pareto front with those presented by Shi et al. [31] are shown to be in a good agreement. Therefore, the proposed algorithm has a good accuracy in prediction of the optimal solutions.

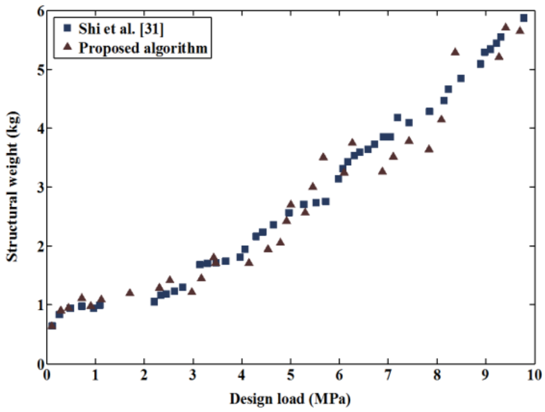

Fig. 20. Comparison between Pareto front obtained by the proposed algorithm and that of Shi et al. [31]

Conclusions

In the present study, a mixed method has been developed for multi-objective optimization of composite structures by coupling genetic algorithm and finite element method. In the proposed algorithm, all the most important parameters in optimization of a laminated composite plate such as, angle, thickness, number, and material of each layer are considered. The buckling load and weight of the laminated composite plate which are defined as objective functions are maximized and minimized, respectively. The proposed algorithm was capable of determining the optimal stacking sequence with a good accuracy and low computational cost. Unlike estimation methods like response surface, in the proposed algorithm, objective functions for each individual are evaluated directly by FEM software which leads to precise results. Therefore, the proposed algorithm provides a reliable and flexible tool to stacking sequence optimization of a laminated composite plate before manufacturing processes. The effect of 3 different types of compressive loads on the optimum buckling load of the laminate composite plate is studied and it is found that the buckling load decreases as the load ratio increases. The effects of boundary conditions and aspect ratio of plate on the optimum design of a laminated composite plate are also investigated. It is deduced from the results that; the effects of boundary conditions are more dominant than the aspect ratio of plate on Pareto front in the buckling of composite plate. Also, it is shown that, composite plate with S-C-S-C boundary conditions has the highest buckling load with respect to others. The validity of the proposed method has been studied by comparison with the results given in the existing literature.

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