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Optimum Buckling Design of Composite Stiffened Panels Using Ant Colony Algorithm

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Abstract: Optimal design of laminated composite stiffened panels of symmetric and balanced layup with different number of T-shape stiffeners is investigated and presented. The stiffened panels are simply supported and subjected to uniform biaxial compressive load. In the optimization for the maximum buckling load without weight penalty, the panel skin and the stiffened laminate stacking sequence, thickness and the height of the stiffeners are chosen as design variables. The optimization is carried out by applying an ant colony algorithm (ACA) with the ply contiguous constraint taken into account. The finite strip method is employed in the buckling analysis of the stiffened panels. The results shows that the buckling load increases dramatically with the number of stiffeners at first, and then has only a small improvement after the number of stiffeners reaches a certain value. An optimal layup of the skin and stiffener laminate has also been obtained by using the ACA. The methods presented in this paper should be applicable to the design of stiffened composite panels in similar loading conditions.

Keywords: composite stiffened panels; laminate stacking sequence; buckling; ant colony algorithm

1. Introduction

Composite materials are becoming increasingly employed in aerospace structures because of their high specific stiffness and specific strength. Since laminated composite stiffened panels are much more efficient in load carrying ability than unstiffened plates, they are widely adapted in aircraft wing and fuselage structural configuration. When a thin composite panel is subjected to compressive load, it could result in global or local buckling as the critical structural failure mode. The stiffeners can enhance the structural stiffness, and therefore the buckling resistance of the structure effectively. To further improve the structural efficiency, optimization of composite stiffened panels to maximize the buckling loads has drawn considerable attention in

recent years. Usually, a composite stiffened panel in aerospace structure comprises of a skin and stiffeners made of different laminate layup. The geometric parameters and stacking sequences of the skin and stiffeners affect the buckling load of the stiffened panel, and hence the optimization of both parameters should be performed simultaneously.

Recently, the optimum buckling design of composite stiffened plate with various stiffeners, loading conditions and aspect ratios has been studied by some researchers using different methods. S.Nagendra [1] proposed an improved genetic algorithm (GA) to find the best stacking sequence of the skin and stiffeners laminate, and the stiffener height for minimum weight of a composite stiffened panel under buckling constraint. In this study, an optimized design with weight saving by about 4% was obtained. In Ref.[2], Ji-Ho Kang, Chun-Gon Kim presented a minimum weight design of composite plates under compressive load and composite stiffened panels under post buckling strength constraint. In this study, the size and location of the stiffeners were considered as the design variables. In Ref.[3], Akira Todoroki presented a stacking sequence optimization to maximize the buckling load of blade-stiffened panels with strength constraint using the iterative fractal branch and bound method. In this procedure, the strength constraint was implemented by means of a response surface. The results show that an optimal stacking sequence of the stiffened panel can be obtained by this method at a low computational cost. In Ref.[4], M.M.Alinia investigated the optimization of plate stiffeners subjected to shear load. The study has shown that the optimum geometric properties of the stiffeners are related to the point when the plate buckling shape changes from a global mode to local mode. M.Walker [5] studied the effect of the stiffener arrangement and boundary conditions on the optimal ply angles and the buckling load. In Ref.[6], Bedair studied the influence of stiffener location on the stability of stiffened plates in compression and plane bending. The results have shown that the optimum location for the stiffener depends on the relative proportions of the plate and the stiffener, and is not always at one fifth of the plate width as recommended by several design specifications. All these previous studies have contributed to useful guidelines, which help the design of stiffened panels under some loading conditions. However, there is no publication focused on the optimum number of stiffeners for the maximum buckling load of composite stiffened panels under weight constraint.

The Ant Colony Algorithm (ACA) is one of the latest heuristic optimization methods.

Inspired by the behavior of ant colonies in foraging food, the method was developed and introduced in early 1990s by Dorigo et al [7]. The search mechanism of ACA is based on the ants' capability of finding the shortest path from a food source to their nest. The ants leave a pheromone trail on their way and each ant chooses its path with respect to the probability depending on the pheromone trails laid by the previous ants. These pheromone trails progressively decrease by evaporation. Each ant probabilistically prefers to choose a path of rich pheromone. The ACA was first applied to the TSP in 1982, and from then its application has been widely extended to other fields of combinatorial optimization problems such as quadratic assignment, vehicle routing and graph coloring. Since then the method has been successfully applied to several Non-deterministic Polynomial (NP) Solvable-difficult combinatorial optimization problems, such as traveling salesman problem (TSP)[8]. ACA was also used to solve some engineering problems such as the feeder bus network design problem [9] and process engineering problems [10]. In Ref.[11], F.Aymerich and M.Serra studied the application of ACA to the layup optimization of laminated panels for maximum buckling load. The results show that the average performance and the robustness of ACA search strategy are comparable or better than that of optimization procedure based on GA or Tabu Search (TS).

As one of the most popular combinatorial optimization problems [12], the traveling salesman problem (TSP) can be described as finding the best order of N cities for a salesman or traveler to visit in the shortest total length of the travel route. Each city must be visited once only. At the end, the traveler must return to the starting city to make a closed loop route. The TSP is a simple combinatorial problem and used as a benchmark method to compare new approaches in combinatorial optimization. Many literatures have been published to study the TSP, many practical problems such as machine scheduling, cellular manufacturing can be easily formulated as a TSP. apart from the basic TSP, some variations TSP such as GTSP (the generalized TSP)[13], TSPP (TSP with Profits)[14] has been introduced to simulate the real word problems.

In this current paper, a modified TSP and ACA is introduced and used for optimum buckling design of laminated composite skin panels with different number of stiffeners without weight penalty. The design variables include ply thickness of the skin and stiffener laminates and the stiffener height. The contiguous ply number no more than four is imposed as constraint.

ESDU a0301[15] program based on finite strip method was used to calculate the buckling load of the composite stiffened panels. The ACA was used to optimize the skin and stiffener ply thickness and the stiffened height.

2. Problem definition

A composite outer wing designed for a multi role large aircraft is taken as the example to demonstrate the analysis and optimization process. As illustrated in Fig.1a, the wing box structure made of composite laminate was divided into 21 thin walled box sections by 22 ribs. T-shape stiffeners were chosen for the upper skin reinforcement. The rib and stiffener pitch were selected based on the design guideline of a conventional wing box configuration in the initial design. In this paper, the upper skin panel of the No. 10 wing box section as illustrated in Fig.1b is taken as an example in the optimization analysis.

The geometric details of the original upper skin panel are shown in Fig.2. The stiffened panel is 2.10m in length and 1.05m in width and comprise of 8 equally spaced T-shape stiffeners. The detailed configuration of the stiffeners is shown in Fig.3. The height of the blade is $H=0.0675\text{m}$, and the width of the flange $b_2=0.07\text{m}$. The skin and stiffener laminate layup is symmetric and balanced and made of 0_2 , ± 45 and 90_2 degree plies considering manufacture constraint. In order to prevent excessive interlamina stress, a ply contiguous constraint was taken to restrict the number of adjacent plies of the same fiber orientation up to four or less. The stiffener blade and flange were constrained to have the same laminate layup.

The stiffened panel is simply supported along the four edges and subjected to compressive load. A reference compressive load of $N_x = 1 \text{ N/m}$ is applied in the x-axis direction. The buckling load of the composite stiffened panels is calculated by using the code in ESDU03001 based on finite strip method [15]. Previous study has shown that the result by using ESDU 03001 agrees with the finite element method very well [16].

The objective of the optimization in the current paper is to find the optimum thickness of the skin and stiffener and the optimum height of the blade to maximize the buckling load of the stiffened panel without weight penalty. The objective function of the optimization is the critical buckling load F_{bcr} of the stiffened panel. The design variables are thickness of the skin panel

T_s , the stiffener blade T_b and flange T_f and the blade height H . In the optimization process, the stiffened panel weight W_{total} or the cross section area of the stiffened plate S , which is proportional to W_{total} is kept constant. To satisfy the weight constraint, the blade height H is taken as a function of the other design variables as expressed below rather than an independent variable.

$$H = \frac{S - b \cdot T_s}{N \cdot T_b} - \frac{b_2 \cdot T_f}{T_b} \quad (1)$$

where N is the number of stiffeners, b is the panel width and b_2 is the stiffener flange width. In order to ensure the laminate is balanced and symmetric and reduce the number of the design variables in the same time, only half of the laminate plies was optimized and the layup was restricted to two ply building stacks in an option of 0_2 , ± 45 and 90_2 . The number of contiguous plies of the same fibre orientation is limited to no more than four in the optimization process. The optimization problem can be formulated as to maximize the critical load F_{cr} of the stiffened panel by finding the optimum thickness and laminate stacking sequence of the skin panel and stiffeners and the blade height.

$$\text{Minimize } F_{obj} = \frac{1}{F_{cr}(T_s, T_b, T_f)} \quad (2)$$

$$\text{Subject to } W_{total} = \text{constant} \quad \text{and } g(\theta) \leq 4$$

where F_{obj} is the objective function, F_{cr} is the critical load of the stiffened panel depending upon the design variables, which is the critical buckling load; $g(\theta)$ is the number of contiguous plies of the same orientation.

3. Implement of the ACA

3.1 ACA coding

As described above, the design variables of the optimization problem in this paper include the thicknesses and laminate stacking sequence of skin and the stiffeners blade and flange. An optimum thickness can be obtained by adjusting the number of plies of the laminate. In the ACA, the three optional ply stacks 0_2 , ± 45 and 90_2 were represented by three codes 1, 2 and 3

in a string respectively. Although the laminate thickness of the skin and stiffeners is varied during the optimization process, the length of the string representing the laminate layup and corresponding to the upper bound of the laminate thicknesses is fixed in the process. To represent laminate layup with a thickness smaller than the upper bound, an empty ply stack represented by E in the string was introduced to change the laminate thickness without altering the string length. Thus, there are four optional stacks 0_2 , ± 45 , 90_2 and an empty stack represented by code 1, 2, 3 and E in the string. Since the empty stack E bit is only used to keep the string in a predefined length, it should be removed first when we encode the string. For example, a string of length 12 {2 2 E 2 1 2 1 1 3 1 1 2} representing a laminate made of up to 48 plies could be encoded for a 44-ply symmetric laminate of $[\pm 45_3/0_2/\pm 45/0_4/90_2/0_4/\pm 45]_s$. In the string, the first code 2 corresponds to the outermost ply stack and the last 2 corresponds to the one closest to the plane of symmetry of the laminate. In this manner, the laminate thickness and layup optimization may be formulated as a combinatorial optimization problem of the four options of the ply stacks 0_2 , 90_2 , ± 45 and E.

For the case of more than one laminate to be optimized, each laminate can be coded as one sub-string and all sub-strings can be put together in a single string to represent all the laminates. For the panel made of two different laminate with the maximum number of ply stacks 7 and 5 for the skin and stiffeners respectively, a single string of 12 bit was created, in which the first 7 bits represents the skin laminate and the second part 5 bits represents the stiffener laminate as illustrated in Fig.4.

3.2 multi city-layer TSP

In this paper, a new version of traveling salesman problem (TSP) called Multi city-layer TSP (MCLTSP) is introduced and a corresponding ACA called MCLACA is developed. The optimization problem of the composite stiffened panel presented in section 2 is modeled as a MCLTSP.

In the MCLTSP, the N cities representing the laminate plies form a city-matrix of city-layers. A 48-ply laminate can be described a 48-city MCLTSP and modeled as a 4×12 city-matrix in 4 lines and 12 columns as shown in Fig.5. The four cities in one column is called a city-layer; the city matrix is called a multi city-layer system. For example, the matrix shown

in Fig.5 is a 12 city-layer system. The traveler must start the tour from one of the cities in the first city-layer and visit each city-layer only once until the last one. The traveler can visit neither the city again in the same city-layer nor any city in a city-layer, which has been visited. In such an open loop route, there is one and only one city being visited in each city-layer. Comparing with the basic TSP, it is noted that not all cities but all the city-layers are visited in MCLTSP. When the traveler reached the last city-layer, the tour was completed and the path can be represented by the city number being visited. Each completed route produces a solution by the MCLTSP. For example, the path shown in Fig.5 can be expressed by $\{2\ 1\ 3\ E\ 1\ 2\ 1\ E\ 1\ 2\ E\ 1\}$ to represent a laminate layup $[\pm 45/0_2/90_2/0_2/\pm 45/0_2/0_2/\pm 45/0_2]$.

To achieve the objective of finding a shortest route corresponding to an optimum laminate stacking sequence, it is necessary to map the laminate optimization process to a MCLTSP. In the laminate optimization, each ply stack has four options $\{E\ 1\ 2\ 3\}$, which can be modeled as a city-layer. Take Fig.5 as example, the 12 city-layer represents the maximum number of ply stacks in the laminate. A complete route containing 12 cities represents one solution for the laminates layup. The length of the path is corresponding to an objective function value in terms of the buckling load of the stiffened panel. In this manner, the composite optimal design problem can be modeled as a MCLTSP. The laminate optimal design problem for the maximum critical buckling load can be transferred to searching for the shortest route in the MCLTSP.

3.3 Multi City Layer Ant Colony Algorithm (MCLACA)

In the current paper, an ACA based algorithm called multi city layer ACA (MCLACA) is presented to apply the ACA to the laminate stacking sequence optimization problem. Similar to the MCLTSP, the cities are grouped into N city layers. Similarly to the basic ACA for TSP, an intensity of trail information is used to simulate the pheromone of ants. We denote the intensity of trail information between city i in the $(N-1)_{th}$ city-layer and city j in the N_{th} layer as $\tau(i, j, N-1)$, where $i, j = 1, 2, \dots, n$, n is the number of cities in a city-layer. Since a priori trail information is not available, we first initiate the intensity matrix of trail information as a fixed number τ_0 . Suppose m is the total number of ants, the ants was initially distributed to the cities in the first city layer randomly in the first step and then all ants move to the city in the

second city layer. For an ant in city i of the $(k-1)_{th}$ city-layer, the probability for the ant to visit the city j in the k_{th} city layer can be written in a formula as follows

$$j = \begin{cases} \arg \max_{j \in allowed_k} \{[\tau(i, j, k)]^\alpha\} & \text{if } q < q_0, \\ S & \text{otherwise,} \end{cases} \quad (3)$$

Where α represents the degree of relative importance of the trail information; q is a value chosen randomly with uniform probability in $[0, 1]$; q_0 is a given parameter and S is a random variable selected according to the following probability distribution, which has a higher level of pheromone trail:

$$P(i, j) = \frac{\tau^\alpha(i, j, k)}{\sum_{u \in allowed_k} \tau^\alpha(i, j, k)} \quad (4)$$

The pheromone trail is updated by two kinds of updating: local updating and global updating. When all ants have completed its tours, if the edge is chosen by an ant m , its amount of pheromone will be changed through the following local trail updating formula:

$$\tau(i, j, k) \leftarrow (1 - \xi) \cdot \tau(i, j, k) + \xi \cdot L(m) \quad (5)$$

where ξ is a parameter, $L(m)$ is the path length of ant m .

Local trail updating is motivated by the trail evaporation of real ants to avoid a high frequency selection of the same route by all the ants that could cause premature solutions and local convergence. When all the ants have completed their tours in an iteration, each ant has a complete path which represents a layup configuration of laminate. Subsequently the objective function in terms of buckling load factor was calculated by using the ESDU 03001 with the result counted as the route length of the corresponding ant in the ACA. The best ant deposits pheromone on the visited edges in its tour while the other edges remain unchanged. The amount of pheromone $\Delta\tau$ deposited on each visited edge by the best ant is proportional to the length of the tour. Global trail updating is similar to a reinforcement learning scheme in which a better solution will obtain a higher reinforcement. The global trail updating formula is expressed by Eq.(6):

$$\tau(i, j, k) \leftarrow (1 - \rho) \cdot \tau(i, j, k) + \Delta\tau \quad (6)$$

$$\rho \in (0,1)$$

$$\Delta\tau = \begin{cases} \rho / L_{gb} & \text{if } (i, j) \in \text{the shortest path} \\ -\varepsilon \cdot \frac{L_{worst}}{L_{best}} & \text{if } (i, j) \in \text{the longest path} \\ 0 & \text{others} \end{cases}$$

The laminate layup symmetry as a constraint is realized by optimizing only half of the laminate with the other half following it. The balanced layup constraint is satisfied by restricting the optional ply stacks to 0_2 , ± 45 and 90_2 . The ply contiguity constraint is satisfied in the selection of the city to visit in the search route. Before visiting a new city, the ant or traveler checks and compares the current city with the previous two cities just visited to avoid selecting the same city as being visited twice continuously. When applied to the laminate optimisation, this process limits the contiguous ply stacks up to two or the number of contiguous plies of the same fibre orientation up to four except for ± 45 plies. For example, a route path [3 2 2 2 1 1] taken by an ant after visiting six city-layers can be encoded as $[90_2/\pm 45/\pm 45/\pm 45/0_2/0_2]$. Since there are four contiguous 0 plies in the current laminate, the next city for the ant to visit can only be selected from {2, 3}. While the city '1' representing " 0_2 " ply stack should be excluded.

The procedure of the MCLACA can be described as follows with its implementation to the laminate stacking sequence optimization problem as illustrated in Fig.6.

- Step 1: Set up parameters and initialize pheromone trails
- Step 2: Allocate the ants to the cities of the first city-layer randomly.
- Step 3: Every ant must walk to a city in the next city-layer depending on the probability distribution given in Eq.(3) or (4)
- Step 4: Perform a local update of pheromone according to Eq.(5)
- Step 5: Calculate the length of all ant paths in terms of laminate buckling load by using the ESDU program; identify the best and the worst ant and perform a global update of pheromone according to Eq.(6)
- Step 6: If the iteration reaches the maximum number, stop the process; otherwise repeat steps 2-5.

4 Results and Discussion

In this paper, a laminate plate was taken as a benchmark case study to validate the proposed MCLACA before applying the method to the optimization of a composite stiffened panel. The study shows the effect of panel laminate stacking sequence, the number and geometry of the stiffeners on the buckling load and optimization of a composite panel.

4.1 Validation of the MCLACA

To validate the proposed MCLACA, a benchmark case study was conducted to maximize the load carrying capability of a simply supported rectangular composite plate. In this case, the critical load for the objective function was either the critical buckling or strain failure load whichever is lower. The carbon/epoxy laminate plate of length $a=508$ mm and width $b=127$ mm is made of $N=48$ plies with ply thickness $t=0.127$ mm and the building ply stacks limited to 0_2 , ± 45 and 90_2 . The laminate material properties are $E_1=127.57$ GPa, $E_2=13.03$ GPa, $G_{12}=6.41$ GPa, $\nu_{12}=0.3$ and the ultimate strains are $\epsilon_1^{ua}=0.008$, $\epsilon_2^{ua}=0.029$, $\gamma_{12}=0.3$. A safety factor of 1.5 is considered in the strength constraint.

The plate is subjected to an in-plane biaxial compressive load λN_x and λN_y , where λ is a load factor. The critical buckling load factor λ_{cb} and the strain failure load factor λ_{cf} is defined as the ratio of the laminate buckling load and strain failure load against the applied load respectively. In this particular stacking sequence optimization, the F_{bcr} in the objective function expressed in Eq.(2) is replaced by the smaller λ_c between the factor λ_{cb} and λ_{cf} corresponding to the maximum buckling load and strain value of the laminate. Three load cases with load ratios of $\lambda N_y / \lambda N_x = 0.125, 0.25, \text{ and } 0.5$ were considered. The symmetric and balanced layup and ply contiguous constraints as described earlier were considered.

The optimal results of the MCLACA in comparison with the results obtained by the GA in Ref.[17] and the B&BL (Branch and bound and linearization) in Ref.[3] are shown in Table 1. The results show that when the load ratio reached $N_y/N_x=0.5$, the failure mode changed from strain failure to buckling failure. The results also indicate that the proposed MCLACA is capable of identifying both failure modes and finding an equivalent or better solution than the GA and B&BL.

Table 1. The Optimization results and comparison between different methods

Optimization method	Laminate stacking sequence	Failure load factor (Mode)
Load Case 1: $N_x=1.0$, $N_y=0.125$		
B&BL	$[\pm 45_3/0_2/(\pm 45/0_4)_2\pm 45/0_2]_s$	13511.33 (strain failure)
GA	$[90_2/\pm 45_2/0_2/(\pm 45/0_2)_4]_s$	13514.13 (strain failure)
MCLACA	$[\pm 45_2/90_2/0_2/\pm 45_2/0_4/(\pm 45/0_2)_2]_s$	13818.29 (strain failure)
Load Case 2: $N_x=1.0$, $N_y=0.25$		
B&BL	$[\pm 45_2/90_2/\pm 45_3/0_4/(\pm 45/0_2)_2]_s$	12622.44 (strain failure)
GA	$[90_2/\pm 45_3/0_2/\pm 45/0_4/\pm 45/0_2]_s$	12674.84 (strain failure)
MCLACA	$[\pm 45_2/90_2/\pm 45_3/0_2/\pm 45/0_4/\pm 45/0_2]_s$	12678.78 (strain failure)
Load Case 3: $N_x=1.0$ $N_y=0.5$		
B&BL	$[90_2/\pm 45_2/90_2/\pm 45/90_2/\pm 45_6]_s$	9998.18 (Bulking)
GA	$[90_2/\pm 45_2/90_2/\pm 45/90_2/\pm 45_6]_s$	9998.18 (Bulking)
MCLACA	$[90_2/\pm 45_2/(90_2/\pm 45)_2/\pm 45_5]_s$	9998.20 (Bulking)

4.2 The stacking sequence optimization of a laminate with and without stiffeners

Following the above benchmark case study, the MCLACA was applied to the optimization of the rectangular composite panel shown in Fig. 1b. The study was started for the skin laminate without stiffeners and then with stiffeners. The dimension of the panel is $a=2.1\text{m}$ in length and $b=1.05\text{m}$ in width. The laminate is made of 72 plies of ply thickness 0.184mm in a symmetric and balanced layup. The plate is simply supported along its four edges and subjected to biaxial compressive forces. The carbon/epoxy IM7 Hexply8552-7 material properties are shown in Table 2. In this case, only the critical buckling load was taken for the objective function without considering the critical strain.

Table 2. The material properties of the laminate plate

E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	ν_{12}
144.00	9.40	4.70	0.30

In the optimization, the laminate stacking sequence under fiber orientation options is chosen as the design variables to achieve the maximum buckling load. The optimization is

subject to the symmetric and balanced layup and ply contiguous constraints as described earlier.

Table 3 shows the optimal results of the plate compared with the initial design.

Table 3. Optimal results of the unstiffened laminated composite plate

Design cases	Stacking sequence	Buckling load (10^5N)
Initial design	$[(\pm 45/0_2/90_2)_6]_s$	3.29
Optimal design	$[((90_2)_2/\pm 45)_6]_s$	5.02

Table 3 shows that the stacking sequence of the laminated plate has a large effect on the buckling load. The 90_2 ply stacks were increased; the 0_2 ply stacks removed; the ± 45 plies remained to satisfy the ply contiguous constraints. As the result, the buckling load of the optimized plate has been increased by 52.6%.

To study the effect of laminate stacking sequence on the buckling load of a stiffened plate, a composite skin panel stiffened by five T-shape stiffeners was investigated. In this case, the materials of the plate remain the same as the above unstiffened plate. In the initial design, the laminate of the skin panel is made of 52 plies and the stiffeners made of 60 plies. The height of the stiffener blade is 78 mm. In the optimization, only the stacking sequence of the skin laminate was selected as design variables within the optional ply stacks. While the geometry of the stiffened panel remains the same as the initial design. The optimization results of the stiffened skin panel were listed in Table 4 to compare with the initial design.

Table 4. Optimization result of the stiffened skin panel

Design cases	Stacking sequence	Buckling load (10^5N)
Initial skin design	$[(\pm 45/0_2/90_2)_4/\pm 45]_s$	37.52
Optimal skin design	$[(90_2)_2/(0_2)_2/90_2/(0_2)_2/(\pm 45)_6]_s$	37.65

Compared with Table 3, the results shown in Table 4 indicate that the stacking sequence optimization of a stiffened skin panel is much less effective for improving buckling load than an unstiffened plate. In this case, an improvement of buckling load by only 0.35% has been achieved for the stiffened skin panel.

4.3 Geometry optimization of the stiffeners of the stiffened panel

As studied in the last section, it is noted that the stacking sequence optimization may significantly improve the buckling capability of a laminate plate. For a stiffened laminate panel however, little improvement of buckling capability was obtained by optimizing the skin laminate stacking sequence. In this current section, the geometry of stiffeners is included in the design variables. Two optimization cases are considered under the constant weight condition. In the first case, only the height and thickness of the stiffeners blade were varied without altering the skin panel and the stiffener flange. In the second case, the skin panel thickness was also included in the design variables. Table 5 shows the results of the two optimization cases in comparison with the original design.

Table 5. The optimization results of the stiffened skin panel

Design case	Skin laminate layup	Stiffener blade laminate layup	Blade height (mm)	Buckling load (10^5 N)
Original	$[(\pm 45/0_2/90_2)_4/\pm 45]_s$	$[(\pm 45/0_2/90_2)_4/\pm 45]_s$	78	37.52
1st case optimization	$[(\pm 45/0_2/90_2)_4/\pm 45]_s$	$[(\pm 45/(0_2)_2/\pm 45/0_2)_2/0_2]_s$	104.91	60.239
2nd case optimization	$[((90_2)_2/\pm 45)_3/\pm 45/(90_2)_2]_s$	$[\pm 45/(0_2)_2/(\pm 45)_2/0_2/90_2/(0_2)_2/\pm 45)_2/0_2/\pm 45]_s$	117.04	101.51

From Table 5, it is clear that the optimization of the height of stiffeners blade is much more effective for the maximum buckling load of the stiffened panel. The buckling load has been increased by 60.56% in case 1 with the height of blade increased from the original design (104.91 vs 78). In the second case, the buckling load has a greater increase by 170.56% from the original design. In this case, the ply number of the skin is reduced from 52 to 48 as the height of the blade increased from 78 to 117.04. It means 7.62% of the mass of the stiffened plate was moved from the skin to the stiffeners without weight penalty.

From the discussion above, we can draw a conclusion that the optimization of stiffeners is much effective to improve the stiffened panel against buckling. From structural point of view, the materials in the stiffeners are much more efficient than the skin in terms of the buckling

stability of the stiffened panel. Therefore in the design of a stiffened panel against buckling, main attention should be paid to the stiffeners design.

4.4 Optimization of the panel with different number of stiffeners

In addition to the optimization of the skin layup and stiffeners geometry, the effect of number of stiffeners on the buckling of the stiffened panel was also investigated. A Matlab program based on the MCLACA was developed and used. This program also employs the ESDU03001 code as a subroutine for buckling analysis and the MCLACA for optimizing the stiffener and skin laminate thickness. The laminate layup of the stiffeners flange and blade was kept identical. While the geometry and number of stiffeners was varied in the optimization without changing the total weight of the stiffened panel. Ten different numbers of stiffeners were considered. The cases with and without the ply contiguous constraint were studied and compared. Since the total length of the string is 40, the total number of city-layer in MCLACA is set to be 40. According to the literature [18], the other parameters chosen in the MCLACA are shown in Table 6.

Table 6. Parameters chosen in the optimization using MCLACA

Parameter	α	q_0	ξ	ϵ	ρ	τ_0	N
Value	0.5	0.8	0.8	0.4	0.6	0.1	40

Table 7 shows the results of the optimum laminate thickness of the skin and stiffeners with different number of stiffeners. It is obvious that as the number of stiffeners increases, the thickness of the skin and stiffeners decreases to maintain the total weight of the panel. As shown in Fig.7, the mass ratio of the skin to the stiffened panel reduces from 65.63% to 43.75% as the number of stiffeners increases from 4 to 13. It indicates that the material used in stiffeners is more efficient than used in skin for improving buckling.

Table 7. Optimum thickness of the skin and stiffeners with different number of stiffeners

Number of stiffeners	Skin thickness (mm)		Blade thickness (mm)		Blade height (mm)	
	A*	B*	A*	B*	A*	B*
4	8.832	8.832	13.984	14.720	117.67	109.72

5	8.832	8.832	11.040	11.776	117.04	106.78
6	8.096	8.096	10.304	11.040	122.45	111.04
7	8.096	8.096	8.832	8.832	120.97	120.97
8	7.360	6.624	8.832	10.304	120.08	114.41
9	7.360	6.624	7.360	8.832	130.69	119.39
10	7.360	6.624	6.624	8.096	129.96	115.37
11	6.624	6.624	6.624	7.360	133.59	114.63
12	5.888	5.888	7.360	7.360	117.36	117.36
13	5.888	5.888	6.624	6.624	121.24	121.24

A*: optimum design with ply contiguous constraints

B*: optimum design without ply contiguous constraints

Fig.8 shows the maximum buckling load of the optimized stiffened panel with different number of stiffeners. The results show that the maximum buckling load of the panel without the ply contiguous constraint is greater than that with the ply contiguous constraint. It is also noted that the influence of ply contiguous on the buckling load becomes smaller as the number of stiffeners increases. This is because the thickness, hence the laminate layup variation of the skin and stiffeners becomes smaller.

As shown in Fig.8, when the number of stiffeners is increased from 4 to 13, the buckling load increases from 80.52 to 205.78 with the ply contiguous constraint and from 107.71 to 207.59 without the ply contiguous constraint. It is shown that the maximum buckling load of a composite stiffened panel can be increased significantly with an optimum number of stiffeners without weight penalty. As shown in Fig.8, when the number of stiffeners was increased from 4 to 5, the skin thickness remained the same, but the maximum buckling load was increased significantly, especially for the case with the ply contiguous constraint. When the number of stiffeners increased up to 9, the maximum buckling load of the stiffened panel kept increasing at a high rate. However the increase slowed down and converged to a value when the number is beyond 9. In this particular case, it seems that 9 stiffeners provide an optimum solution. In practice, the number of the stiffeners is limited by the overall structure configuration, assembly and manufacture consideration.

Instead of optimizing the geometry and laminate layup of the skin and stiffeners separately, study was also carried out by optimizing all the design variables simultaneously by using the

MCLACA. The optimization results are shown in Table 8 and 9.

Table 8. Optimized laminate layup of the skin and stiffeners with the ply contiguous constraint

Stiffener number	plies	Laminate layup		Buckling load (10 ⁵ N)
		S: skin	B: blade and flange	
4	S-[48]	[((90 ₂) ₂ / ±45) ₂ /90 ₂ / ±45/ (90 ₂) ₂ / (±45) ₂] _s		80.52
	B-[76]	[(±45) ₄ /(0 ₂) ₂ /±45/(0 ₂) ₂ /90 ₂ /(0 ₂) ₂ /±45/(0 ₂) ₂ /90 ₂ /±45/(0 ₂) ₂] _s		
5	S-[48]	[((90 ₂) ₂ / ±45) ₃ / ±45/ (90 ₂) ₂] _s		101.51
	B-[60]	[±45/(0 ₂) ₂ /(±45) ₂ /0 ₂ /90 ₂ /((0 ₂) ₂ /±45) ₂ /0 ₂ / ±45] _s		
6	S-[44]	[((90 ₂) ₂ / ±45) ₂ /(90 ₂) ₂ /0 ₂ /90 ₂ /0 ₂] _s		125.78
	B-[60]	[(±45) ₃ /0 ₂ /(±45) ₂ /(0 ₂) ₂ /±45/(0 ₂) ₂ /90 ₂ /(0 ₂) ₂] _s		
7	S-[44]	[(90 ₂) ₂ /0 ₂ /(90 ₂) ₂ / ±45/90 ₂ /(0 ₂) ₂ /±45/0 ₂] _s		161.19
	B-[48]	[0 ₂ /(90 ₂) ₂ /±45/(0 ₂) ₂ /90 ₂ /(0 ₂) ₂ /±45/0 ₂ /±45] _s		
8	S-[40]	[(90 ₂) ₂ /0 ₂ /(90 ₂) ₂ / ±45/(0 ₂) ₂ /±45/0 ₂] _s		176.17
	B-[48]	[90 ₂ /0 ₂ /90 ₂ /(0 ₂) ₂ / (±45/(0 ₂) ₂) ₂ /±45] _s		
9	S-[40]	[((90 ₂) ₂ /0 ₂) ₂ /0 ₂ /±45/(0 ₂) ₂] _s		189.9
	B-[40]	[(90 ₂) ₂ /(0 ₂) ₂ /90 ₂ /(0 ₂ /±45) ₂ /0 ₂] _s		
10	S-[40]	[(90 ₂) ₂ /0 ₂ /90 ₂ /0 ₂ /±45/0 ₂ /±45/(0 ₂) ₂] _s		190.6
	B-[36]	[(90 ₂) ₂ /(0 ₂) ₂ /90 ₂ /(0 ₂) ₂ /(±45) ₂] _s		
11	S-[36]	[(90 ₂) ₂ /(0 ₂) ₂ /90 ₂ /0 ₂ /±45/(0 ₂) ₂] _s		192.97
	B-[36]	[(90 ₂) ₂ /(0 ₂) ₂ /90 ₂ /0 ₂ /(±45) ₂] _s		
12	S-[32]	[(90 ₂) ₂ /0 ₂ /90 ₂ /0 ₂ /±45/(0 ₂) ₂] _s		205.21
	B-[40]	[90 ₂ /0 ₂ /90 ₂ /(0 ₂) ₂ /±45] _s		
13	S-[32]	[(90 ₂) ₂ /0 ₂ /90 ₂ /(0 ₂) ₂ /±45/(0 ₂) ₂ /±45/0 ₂] _s		205.78
	B-[36]	[90 ₂ /0 ₂ /90 ₂ /(0 ₂) ₂ /±45] _s		

Table 9. Optimized laminate layup of the skin and stiffeners without ply contiguous constraint

Stiffener number	plies	Laminate layup		Buckling load (10 ⁵ N)
		S: skin	B: blade and flange	
4	S-[48]	[[$(90_2)_{11}/\pm 45$] _s]		107.71
	B-[80]	[$0_2/90_2/0_2/\pm 45/90_2/\pm 45/(0_2)_3/(\pm 45/(0_2)_4)_2/0_2$] _s		
5	S-[40]	[[$(90_2)_4/0_2/90_2/\pm 45/(90_2)_2/\pm 45/0_2/(0_2)_3/\pm 45/(0_2)_3$] _s]		116.7
	B-[80]	[$0_2/\pm 45/0_2/90_2/(0_2)_2/90_2/0_2/\pm 45$] _s		
6	S-[44]	[[$(90_2)_5/(0_2)_2/(\pm 45)_3/0_2$] _s]		147.88
	B-[60]	[$90_2/(0_2)_4/\pm 45/0_2/\pm 45/(0_2)_2/\pm 45/(0_2)_4$] _s		
7	S-[44]	[[$(90_2)_5/(0_2)_3/(\pm 45)_3$] _s]		167.13
	B-[48]	[$90_2/0_2/\pm 45/0_2/90_2/(0_2)_4/\pm 45/(0_2)_2$] _s		
8	S-[36]	[[$(90_2)_5/(0_2)_2/\pm 45/(0_2)_2$] _s]		183.37
	B-[56]	[$0_2/90_2/\pm 45/90_2/(0_2)_5/\pm 45/(0_2)_2/\pm 45/0_2$] _s		
9	S-[36]	[[$(90_2)_4/0_2/\pm 45/(0_2)_3$] _s]		191.00
	B-[48]	[$(0_2)_2/(90_2)_2/(0_2)_2/\pm 45/0_2/(\pm 45)_2/(0_2)_2$] _s		
10	S-[36]	[[$(90_2)_2/0_2/90_2/0_2/\pm 45/(0_2)_3$] _s]		195.28
	B-[44]	[$90_2/(0_2)_3/90_2/\pm 45/(0_2)_2/\pm 45/(0_2)_2$] _s		
11	S-[36]	[[$(90_2)_2/0_2/90_2/\pm 45/(0_2)_4$] _s]		195.74
	B-[40]	[$(0_2/90_2)_2/\pm 45/(0_2)_3/\pm 45/0_2$] _s		
12	S-[32]	[[$(90_2)_3/(0_2)_3/\pm 45/0_2$] _s]		206.86
	B-[40]	[$(90_2/0_2)_2/0_2/(0_2/\pm 45)_2/0_2$] _s		
13	S-[32]	[[$(90_2)_3/(0_2)_5$] _s]		207.59
	B-[36]	[$90_2/(0_2)_2/90_2/0_2/\pm 45/0_2/\pm 45/0_2$] _s		

5 Conclusions

This current paper focused on the optimization of a composite plate and a T-shape stringer

stiffened panel for the maximizing the buckling load under a given weight. The design variables include the geometry and laminate layup of the skin and stiffeners with the ply contiguous constraint. A modified ant colony algorithm called MCLACA was presented and applied to optimize the plate and stiffened panel. It is proved that this optimization method combined with the ESDU-a0301 program for buckling calculation is a very efficient design tool in the application. From the study results, the following conclusions can be drawn. For a composite plate, the maximum buckling load can be increased significantly by optimizing the laminate stacking sequence without weight penalty. For a stiffened panel, the effect of skin and stiffener laminate layup on the overall buckling is much smaller than the stiffeners geometry, especially the blade height. In addition, the number of stiffeners of the panel has the largest influence on the buckling load of the panel. The maximum buckling load of the stiffened panel increases with the number of stiffeners without weight penalty and converge to a value. Without the ply contiguous constraint, the maximum buckling load of the optimized panel is normally greater than that with the ply contiguous constraint. The proposed MCLACA can also be applied to the case of optimizing the geometry and laminate layup of the skin and stiffeners of a stiffened panel simultaneously for the maximum buckling load under a weight constraint.

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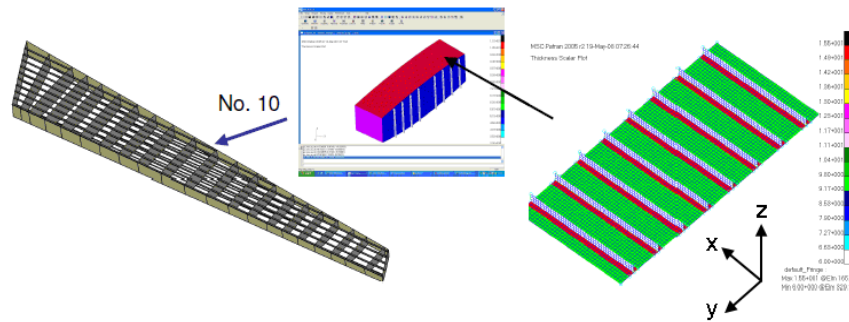


Fig. 1. (a). A composite outer wing box; (b). An upper wing stringer-skin panel

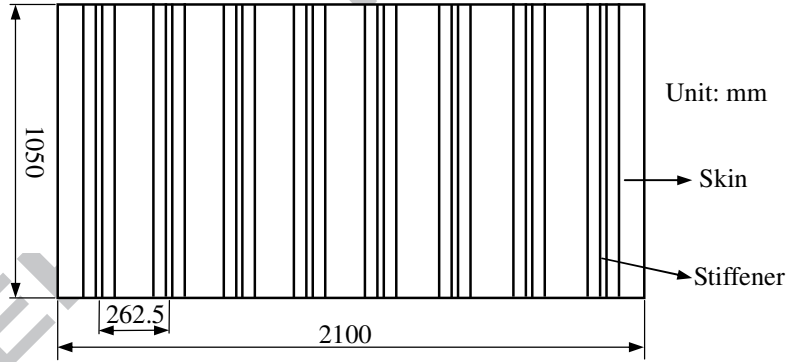


Fig. 2. Geometry of T-type stiffened panel

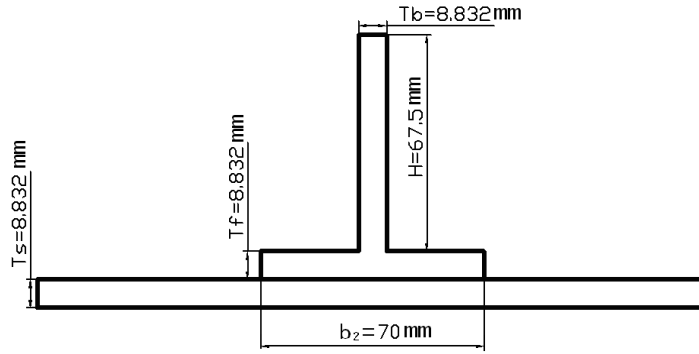


Fig 3. Laminate thickness and geometric parameters of the T shape stringer

Coding $\underbrace{2 \ 1 \ 3 \ E \ 1 \ 2 \ 1}_{\text{first laminate}} \ \underbrace{E \ 1 \ 2 \ E \ 1}_{\text{second laminate}}$

Encoding $[\pm 45/0_2/90_2/0_2/\pm 45/0_2] \ [0_2/\pm 45/0_2]$

Fig. 4 illustrate of the long string

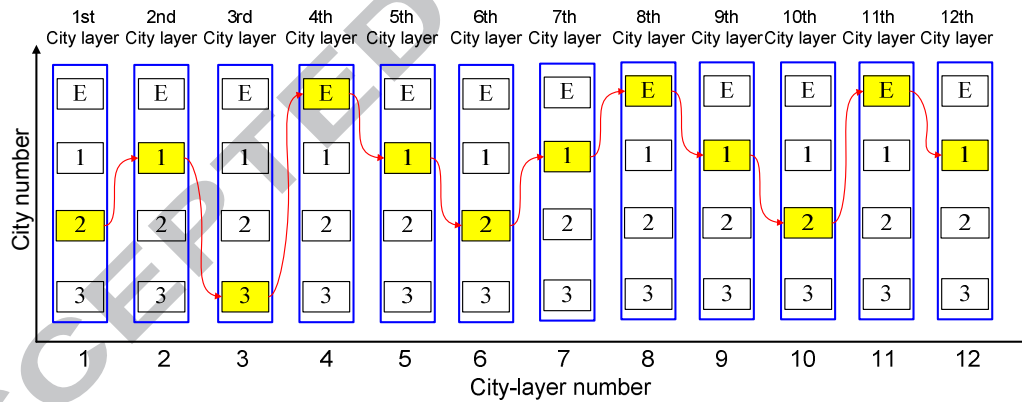


Fig.5 illustrate of the multi city-layer system

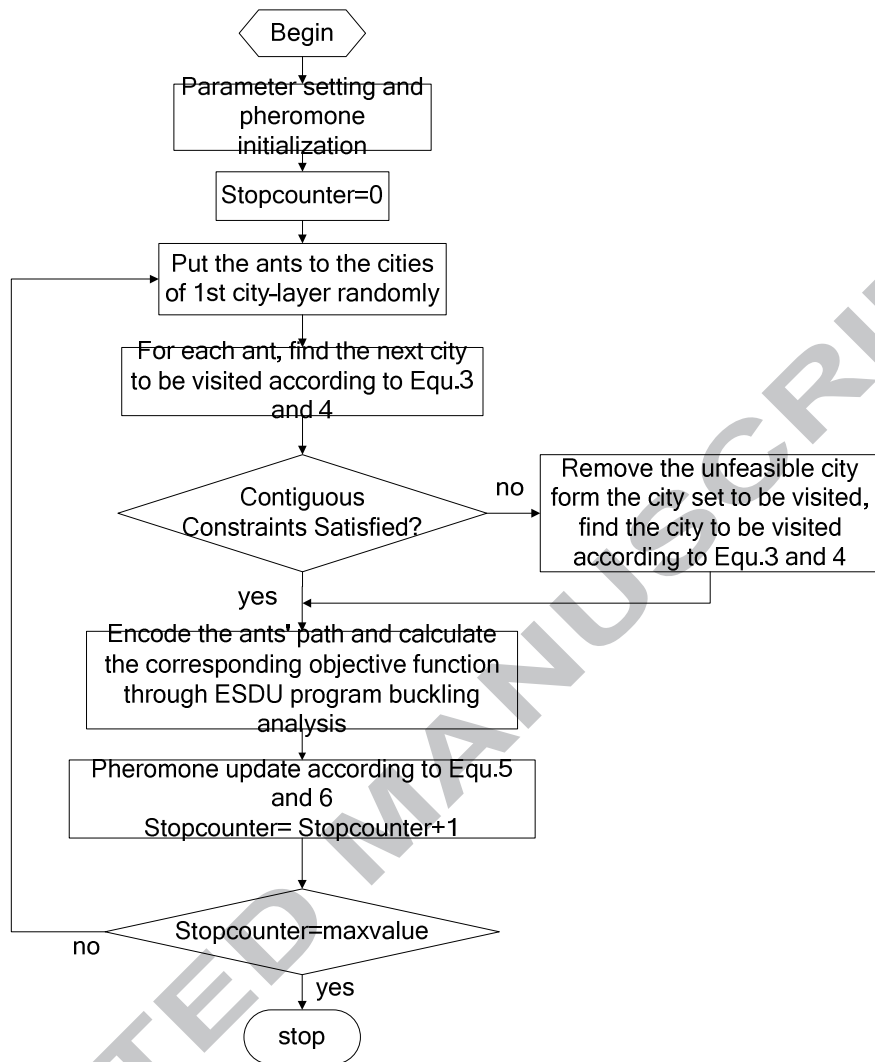


Fig.6 flowchart of MCLACA

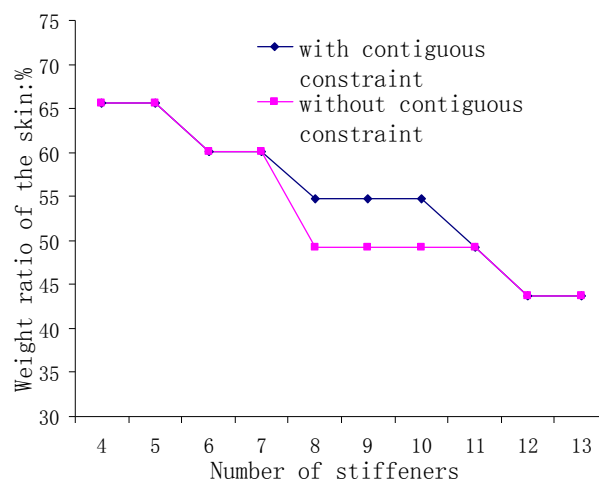


Fig. 7 weight ratio of the skin and stiffened panel with different number of stiffeners

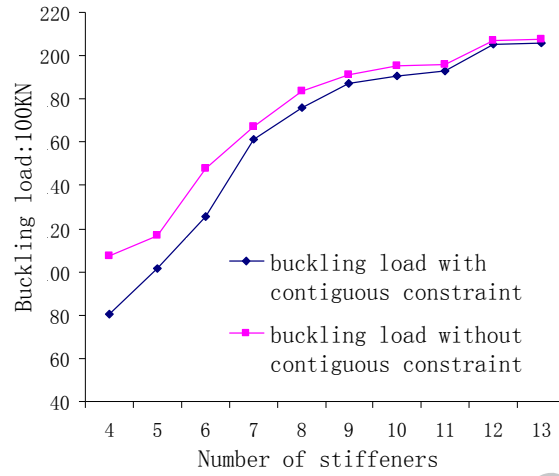


Fig. 8 Maximum buckling load of the stiffened panel with different number of stiffeners

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