Global shared-layer blending method for stacking sequence optimization
design and blending of composite structures

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A global shared-layer blending (GSLB) method is proposed for obtaining manufacturable stacking
sequence of composite structures with blending and design rules. The method combines the traditional
SLB technique with an evaluation algorithm of spatial variation of panels, where the manufacturability of
laminates is enhanced by identifying and minimizing the ply-drops, and controlling the laminate transi-
tion drop boundaries. In addition, a blended design scheme is also proposed, which is achieved by using
the stacking sequence table technique. A composite wing structure is selected to validate the efficiency
and accuracy of the proposed method. Results show that the GSLB method can be used for generating
more manufacturable designs of large-scale composite structure with multiple engineering constraints.

1. Introduction

Composites have now gained wide acceptance and validation in aerospace applications due to their high stiffness to weight and strength to weight ratios [1–5]. Their variable thicknesses and fiber orientations ensure high designability, thus provide alternative choices in the design of many aerospace structure parts [6,7]. The design of large composite structures is usually based on the subdivision of the overall structure into local panel design problems [8,9], in which the material composition of each laminate and the stacking sequence of the plies are determined at the global and the local levels, respectively. For instance, aircraft wings and fuselage skins are often divided into panels or regions with decreasing thickness aiming to a weight reduction under varying loads (Fig. 1). In these variable stiffness composite structures, the arrangement of the constituent materials varies from one region within the structure to another and thus numerous design variables are needed to represent the spatial variation in stacking sequence. Therefore, stiffness variations between panels can be achieved by modifying the thickness, the ply orientation and the stacking sequence. However, the variation of layer thickness, the mismatches of ply orientations and stacking sequences often lead to ply-drops between adjacent panels. From the mechanical perspective, ply-drops break the load path in the structure, thus cause out-of-plane stress concentrations in tapers which may lead to inplane delamination. Moreover, discontinuity of layers causes loss of integrity as well as increases the manufacturing difficulty and cost [10–12].

In manufacturing process, both blending and design rules should be considered [13,14]. The design rules define the sequence layout at the local level, where the penalty method is commonly used to satisfy these rules with the buckling load as the objective function [15–18]. However, the penalty method has the drawback of being unable to satisfy all the design rules simultaneously due to the combinatorial nature of these constraints. The blending rules define the layer continuity between adjacent panels from local level to global level. The blending methodology was first developed by Kristinsdottir et al. [19] to measure the ply compatibility between adjacent panels, which incorporated varying loads in the optimal design process to ensure the continuity and manufacturability. Later, a two-step design procedure for blended stacking sequence was presented and implemented in software using the genetic algorithm (GA) [20], in which the concepts of sub-laminates and design variable zones were introduced. One of the most successful definitions for blending laminates originates from Adams et al. [21–23], in which the concept of guide-based design was introduced to construct globally blended structure. In recent years, inward and outward blending methods were developed by Seresta et al. [24] to improve the ply continuity between adjacent panels by imposing the blending constraints. Ijsselmuiden et al. [25] proposed a multi-step method for design of composite panels
where discrete blended stacking sequences were obtained using a guide-based GA. However, since the stacking sequence of the thinnest region is imposed on all other regions the guide-based approach, inward and outward methods do not provide high flexibility in the design of blending.

To improve the structural efficiency, some efforts have been made for generating blended structures [26–32]. An attempt to obtain global ply compatibility was made by Liu et al. [29,30] using a stacking-sequence table (SST) technique. Recently, Liu et al. [9,32] proposed a blending scheme, referred as shared-layer blending (SLB) method, where the sequences of the regions were arranged into sets of plies that satisfy the blending rules, then the permutation GA was adopted in sequence optimization. Most recently, the optimal design of composite laminate structure with ply-drops [10] was represented using the SST method combined with a thickness distribution over the regions of the structure, in which evolutionary algorithm (EA) is used to obtain the optimal stacking sequence with multiple engineering constraints. As pointed out in Refs. [26,27] that the backtracking method imposed the stacking sequences of the thinnest panel to the entire regions. However, GA, EA and backtracking method are computationally expensive, making them not suitable for large-scale composite structure optimization problem. Moreover, it is also difficult to achieve an optimal solution with complex discrete constraints using penalty function method and therefore it does not guarantee the satisfaction of all the design and blending rules.

Most of the previous researchers focused their attentions on solving the blending problem from local level to global level, because blending rule is defined as the continuity of layers between two adjacent panels. As stated above, one successful approach consider the blending problem from global level to local level is the SLB method, where the blending rules is satisfied at the global level (Fig. 2). Previous researches have proved that with this method the stress concentration caused by ply-drops can be released effectively by ensuring blending requirement between panels [20,24]. Intrinsically, the maximum blending structure with different ply shapes can be evaluated using the SLB method since ply shape can be identified by the thickness distribution of each ply orientation. However, since only the shared layers in adjacent regions can be identified, which makes the blending scheme only applicable between those panels belong to an integrated region, the SLB method may fail to predict the distribution of remaining layers when the covered underlying panels distribute in several separated subregions, which obstacles its extensive application in engineering. The objective of this work is to extend the original SLB method to consider the shared layers among local regions, which is achieved by combing a ply-panel continuity algorithm with the SLB scheme. The blending design scheme and the stacking sequence design method are introduced in Sections 2 and 3, respectively. In Section 4, a benchmark problem is used to validate the modified method. Finally, some conclusions are made in Section 5.

2. Blending design scheme

2.1. Shared-layer blending (SLB)

The SLB method was proposed by Liu and Toropov [9,32], where the laminate parameters were obtained from the global level and SLB process was performed to satisfy the blending rules as well as the general lay-up design rules.

The SLB scheme consists of the following steps [9]. First, rank all panels in terms of ply numbers for each ply angle. Second, find the minimum number of plies out of all panels for each ply angle, which is identified as the first set of shared layers among all panels. Besides, the panel with thinnest layer that contains the first shared layers should be identified and the remaining layers are determined by subtracting the first shared layers from each panel. Finally, the panel with thinnest layer is removed from the entire region. Following the above steps, find the second shared layer among the remaining panels. Repeating this procedure until the last panel is considered. After the global blending among all panels, the local blending between adjacent panels should be performed for all layers, which makes the outer layers continuously cover all panels, known as outer blending (Fig. 3). Otherwise, the inner blending will be obtained with the maximum continuous layers placed from the position next to the mid plane to the outermost position. Considering the damage tolerance requirements of practical composite structures, the outer blending scheme is usually adopted.

2.2. Global shared-layer blending (GSLB)

2.2.1. Regional continuity

In this work, a labeled graph is used to characterize the continuity of a multi-panel structure, where each panel can be treated as a point in a labeled graph. The continuity of a graph can be well defined by the adjacent matrix of all points. Considering a graph of n labeled points, the adjacent matrix A will be a n × n matrix, where the components of the matrix a<sub>ij</sub> equals one if point v<sub>i</sub> is adjacent to point v<sub>j</sub>, otherwise a<sub>ij</sub> equals zero. Thus, the labeled graph G with n points has one to one mapping relation with an n order symmetric matrix A. Besides, matrix A is a symmetric matrix with only zero and unit elements and the diagonal elements are zeroes. A nine-panel structure and its corresponding labeled graph are shown in Fig. 4. Eq. (1) is the adjacent matrix of the nine-panels, which shows the continuous relation of the panels.
In SLB scheme, after each blending operation, the thinnest panel is removed from the region and thus the relation among panels should be updated accordingly, which makes the remaining layers been divided into several subregions. Besides, the panels in each subregion connect with each other while are separated from those in other subregions. Thus, to successfully perform the SLB scheme the distribution of the remaining layers must be identified. Therefore, it is essential to detect the layer distribution in the entire region after every SLB operation. Fig. 5 shows the subregion detect processes, in which the proposed ply-panel continuity algorithm is demonstrated.

In the ply-panel continuity algorithm, the adjacent matrix and the number of shared panels serve as the initialization parameters. Assume the total number of panels to be \( P \). All shared panels are divided into four groups: checked panels, unchecked panels, connected panels, and appeared panels. Checked panels group is used to record the panels that have been checked; connected panels group is used to record the panels connected to the current panel; appeared panels group is used to record all of the panels in the checked panels group and the connected panels of the checked panels group; the unchecked panels group is used to record the unchecked panels. It should be clarified that both the checked panels group and connected panels group are the subsets of the appeared panels group.

Check the panels from 1 to \( P \),

1. Add the current panel to the checked panels group and appeared panels group simultaneously. If the current panel, defined as the channel to be checked, has connecting panels, update all of the panels in the connected panels group and add them to the appeared panels group, turn to II; Otherwise, turn to III.

Fig. 3. Illustration of shared-layer blending (SLB) concept for composite laminate structure.

Fig. 4. A nine-panel structure and its corresponding labeled graph.

\[
A = \begin{bmatrix} 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
2 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
3 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
4 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\
5 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
6 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\
7 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\
8 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
9 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
\end{bmatrix}
\]  

(1)

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Fig. 5. Flowchart of the ply-panel continuity algorithm.
II. Check the connected panels group, if there are panels unchecked, make the first one as the current panel, then turn to I; Otherwise turn to III.

III. Check the appeared panels group, if there are panels unchecked, make the first one as the current panel, turn to I; Otherwise, all panels in the appeared panels group assemble a new subregion $R_i$, record the subregion and the terminated panel, turn to IV.

IV. Remove the panels in the appeared panels group from the unchecked panels group. Check the unchecked panels group, if there are panels unchecked, make the first one as the current panel and clear the other three panels group, turn to I; Otherwise, the unchecked panels group is empty, all panels have been checked. Output all subregions $R_1, R_2, \ldots, R_n$ with terminated panels, respectively.

2.2.2. Global blending rule

A ply-panel continuity algorithm is implemented in the SLB scheme, where the blending rules are performed at the global level and thus is called global shared-layer blending (GSLB) method. In this method, the thickness distribution of panels is evaluated by SLB which guarantees the maximum continuity property among different subregions. In addition, to make the output adapt to manufacturing, the ply-panel continuity algorithm is included to evaluate the shared-layer distribution among divided subregions. A flowchart of the GSLB method is shown in Fig. 6, and the process includes the following steps.

I. Input the initial data: input the adjacent matrix and the ply number of each orientation.

II. Find the shared panels of the current region: for orientation $\theta$ plies, out of all panels find the panel with a minimum number of $\theta$ plies, make the number as the shared layer number and these panels with more layers than the shared layer as the shared panels.

III. Detect the continuity property of the shared panels. Based on the updated shared panels information of the adjacent matrix, detect the distribution of the shared layer using the ply-panel continuity algorithm. The shared layers may be divided into several subregions: $R_1, R_2, \ldots, R_n$.

IV. Update the adjacent matrix and region. Start from the new subregion $R_j$ ($j=1,2,\ldots,n$). Subtract the number of shared layers of $\theta$ plies from all panels. If the number of $\theta$ plies of any panel becomes 0, the panel is removed in the following process by deleting its corresponding row and column elements in the adjacent matrix. Moreover, the panels to be analyzed are also updated by removing the panels without any $\theta$ plies.

V. Check the remaining panels. If the remaining panels in subregion $R_j$ have any $\theta$ plies left, turn to II; Otherwise, the shared process for subregion $R_j$ is over, turn to VI.

VI. Check subregions. If all subregions have been detected, turn to VII; Otherwise, $j=j+1$, turn to IV.

VII. Check all the orientation angles. If all plies of orientation $\theta$ have been detected, $\theta=\theta+1$, turn to II; Otherwise, finish the GSLB process.

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III. Check the appeared panels group, if there are panels unchecked, make the first one as the current panel, turn to I; Otherwise, all panels in the appeared panels group assemble a new subregion $R_i$, record the subregion and the terminate panel, turn to IV.

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III. Detect the continuity property of the shared panels. Based on the updated shared panels information of the adjacent matrix, detect the distribution of the shared layer using the ply-panel continuity algorithm. The shared layers may be divided into several subregions: $R_1, R_2, \ldots, R_n$.

IV. Update the adjacent matrix and region. Start from the new subregion $R_j$ ($j=1,2,\ldots,n$). Subtract the number of shared layers of $\theta$ plies from all panels. If the number of $\theta$ plies of any panel becomes 0, the panel is removed in the following process by deleting its corresponding row and column elements in the adjacent matrix. Moreover, the panels to be analyzed are also updated by removing the panels without any $\theta$ plies.

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Fig. 6. Flowchart of the global shared-layer blending (GSLB) method.

Fig. 7. Comparison between GSLB and SLB searching processes of a nine-panel problem.
As described above, the difference between GSLB and SLB is that GSLB takes advantage of the ply-panel continuity algorithm and thus can evaluate the shared layers distribution in divided subregions. To demonstrate the difference between the two methods, a nine-panel model with same orientation plies (Fig. 4) is analyzed. The panel continuity and the adjacent matrix are shown in Fig. 4 and Eq. (1), respectively. The output of each blending operation is presented and a comparison of the searching process and the subregions evaluated by the ply-panel continuity algorithm are shown in Fig. 7. The changing process of thickness of the two methods is shown in Table 1 as well as the subregions evaluated by the ply-panel continuity algorithm shown in Fig. 7. Note that a parameter $R_{ij}^{h}$ is defined to represent the new regions after the shared layers found by GSLB, where superscript $\theta$ is the orientation angle, subscript $i$ is the operation time and subscript $j$ is the subregion number.

As shown in Fig. 7, at the 4th blending operation, the shared layers distribute in two subregions. Without consideration of the layer distribution, the SLB makes the layer as an integrated continuity region and finds the shared layer among all of the panels between two divided regions, which results in a misjudgment of the shared layer from the 5th time. This phenomenon occurs commonly in multi-panel composite structures, especially for large-scale composite structures of many stacking plies in engineering fields. This drawback of SLB limits its application in composite structures design. In contrast, the GSLB method is capable of achieving the

<table>
<thead>
<tr>
<th>Panel number</th>
<th>Ply numbers of $\theta$</th>
<th>Shared layers blending operation</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>2nd</td>
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<tr>
<td>1</td>
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Table 1
Comparison of GSLB and SLB searching process.

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layer distribution among divided subregions with different ply shapes and thus can be applied in complex engineering structures.

3. Stacking sequence design

One strategy for achieving a blended structure is to limit the variation of the lamination sequences by enforcing continuity constraints in adjacent elements. The continuity requirement is commonly referred to as the blending rules in composite structures design. Over the past decades, the guide-based blending concept [21–23], the backtracking method [26,27], and the SST [10] are used successfully in solving the blending problem. All of the methods mentioned above guarantee the continuity requirements from local level to global level, in other words from the thinnest region spread over the whole structure by adding plies from the thinner laminate to the thicker one. However, the stacking sequence has significant influence on the blending design since it is a highly constrained problem and in some cases the continuous plies interact with each other between adjacent panels. In order to obtain the blending design, the SST tries to find a balance solution between weight reduction and blending requirements. The final results show that it obtained a total blended structure with some weight increase. Conversely, in this work, we assume that the structural weight is constant which means the thicknesses of panels are fixed, and the maximum blending structure is obtained with constant weight. Furthermore, we consider the blending requirement and stacking sequence respectively and the stacking sequence of each panel can be designed from global level to local level by combing the SST with the GSLB results (Fig. 2).

3.1. Design rules

Laminate design starts from selecting the set of ply angles relevant to a given application. Due to manufacturing constraints, the fiber orientation in each ply is commonly one of the following values: \{0°, ±45°, 45°, 90°\}. The design rules consist in assigning an orientation to each ply in the structure such that the following rules are satisfied [10,27].

r1 Symmetry: stacking sequences should be symmetric about the mid plane.

r2 Balance: stacking sequence should be balanced, with the same number of +\(\theta\) and −\(\theta\) plies (\(\theta \neq 0\) and \(\theta \neq 90°\)).

r3 Contiguity: no more than \(m (m \leq 4)\) given number of plies of the same orientation should be stacked together.

r4 Disorientation: the difference between the orientations of two consecutive plies should not exceed 45°.

r5 10%-rule: a minimal of 10% of plies in each of the 0°, ±45°, 45° and 90° orientation is required.

r6 Covering: covering plies on the lower and upper surfaces of the laminate should not be dropped.

r7 Fixed thickness: a fixed number of plies of each orientation are defined in each panel. These numbers of plies are the results of a preliminary optimization with the orientation percentages as design variables.

r8 Uniform distribution: the global shared-layers are stacked first, subregion shared-layers should be insert between different global shared-layers to make them distributed uniform in the whole structure.

![Fig. 9. Schematic of a-25 panel composite horizontal tail structure.](image-url)

<table>
<thead>
<tr>
<th>Table 2</th>
<th>GSLB searching process for the horizontal tail structure.</th>
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<tbody>
<tr>
<td>Panel number</td>
<td>Plies per (\alpha N_0, N_{\pm 45}, N_{90})</td>
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3.2. GSLB based stacking sequence table (SST)

From the GSLB scheme, the structure with fixed thicknesses of panels and maximum continuity regions can be evaluated without considering the stacking sequence. In the following stacking sequence design, to satisfy the blending requirements, every global shared-layer or subregion shared-layer should not be divided.

In this paper, the SST technique is adopted to satisfy all of the requirements mentioned in Section 3.1. In SST, each layer is used as an integrated part and be inserted into the whole structures one by one to satisfy design rules. Thus, if any violation of the design rules occurs among all the panels the shared-layer covers, the shared-layer should be inserted into another stacking position. As is shown in Fig. 8, a nine-panel model built in Fig. 4 is used to show this procedure, different orientation plies are included in the illustration. According to the uniform distribution requirement, firstly, the global shared-layer should stack uniformly in the structure, secondly, the subregion shared-layers are inserted between global shared-layers from the largest one to the second largest. As shown in Fig. 8(b), the first subregion shared-layer can only be inserted between global shared-layers 4 and 5, because all stacking positions between 1 to 4 violate the design rule r3 (when \( m = 2 \)), the position between 5 and 6 is not available since it violates the design rule of r4. For others subregion shared-layers, the process are the same. When a shared-layer is inserted into a stacking position, all design rules should be satisfied. The final results are shown in Fig. 8(f), where all subregion shared-layers are inserted without any violation of the design rules.

The GSLB results contain information of the shared-layer distribution according to the thickness distribution of each ply angle. Based on the GSLB results, the uniform distribution requirement can be introduced in the design process, where both the global shared-layers distribute uniformly in the structure and the subregion shared-layers are included. Uniform distribution layer structure can smooth the load distribution over the structure and thus avoid high stress concentrations at dropped plies, especially interlaminar stress. As a result, the GSLB encompasses the SST under the requirement of uniform distribution, which provides a more detailed description of the layout of the shared-layers over the structure. Additionally, satisfaction of the design rules can be assessed using the GSLB based SST technique.

4. Numerical experiment

A composite horizontal tail structure shown in Fig. 9 is selected as a benchmark problem to validate the proposed GSLB method. Considering the structural efficiency of the horizontal tail, the entire region are divided into 25 panels with varying thickness,
where ply numbers of each orientation are presented in Table 2. The symmetry, balance and 10%-rule are taken into account according to the design rules. Thus, the number of pairs of ±45° plies is presented as \( N_{45} \), half number of the composite laminate plies \( N \) equals to \( N_0 + 2N_{45} + N_{90} \), with \( N_0, N_{45}, N_{90} \) to be half of the ply number in orientation of 0°, ±45°, and 90°, respectively.

The components of the adjacent matrix can be determined and serve as the initialization information accompanied with the ply numbers of each panel. Following the flowchart of GSLB method, the shared-layers are searched for each ply angle and the procedure is shown in Table 2 and Fig. 10.

From the summarized GSLB results of the studied composite structure, there are 18 subregions and each region have several shared-layers, for example \( R_{01} \) have two 0 orientation shared-layers, while \( R_{451} \) have two pairs of ±45 orientation shared-layers. Therefore, there are 28 shared-layers in the whole structure. Combining the GSLB results with SST technology, two stacking sequence solutions of the horizontal tail structure are obtained, as shown in Tables 3 and 4, which satisfy all of the design rules. As required of uniform distribution, the global shared-layers are first stacked together with green rows in the two tables, and then all of the subregion shared-layers are inserted one by one from the largest one to the second largest one among the global shared-layers. Besides, the thicknesses of panels among the region are fixed, which makes the design rule of r3 is flexibly satisfied. Thus, two same orientation layers \( (m = 2) \) stack together is used as the design rule of r3 in all of the panels. If the shared-layer cannot be inserted into any two layers, three same orientation layers can be stacked together and hence the shared-layer can be inserted. As a result, in both solutions, all of the positions satisfy the r3 rule with two layers stack together except for these positions in the dashed box, in which three 0 orientation layers are stacking together. Additionally, in solution 1, at the mid-plane two 45 layers stack together resulting in four 45 layers stack together in the whole structure. In contrast, in solution 2, there is only one 0 global shared-layer stacks at the mid-plane, resulting in two 0 layers stack together in the whole structure. Even though, both solutions fully satisfy the design rules with a very low computational cost of 0.06s. The algorithm is implemented in Matlab.

### Table 3

<table>
<thead>
<tr>
<th>( R_{0} )</th>
<th>Stacking sequence of all panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>( R_{45} )</td>
<td>-45</td>
</tr>
<tr>
<td>( R_{1} )</td>
<td>0</td>
</tr>
<tr>
<td>( R_{2} )</td>
<td>45</td>
</tr>
<tr>
<td>( R_{0} )</td>
<td>0</td>
</tr>
<tr>
<td>( R_{0} )</td>
<td>45</td>
</tr>
<tr>
<td>( R_{2} )</td>
<td>90</td>
</tr>
<tr>
<td>( R_{0} )</td>
<td>90</td>
</tr>
<tr>
<td>( R_{2} )</td>
<td>45</td>
</tr>
<tr>
<td>( R_{45} )</td>
<td>0</td>
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<tr>
<td>( R_{0} )</td>
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</tr>
<tr>
<td>( R_{0} )</td>
<td>45</td>
</tr>
</tbody>
</table>

5. Conclusions

Stacking sequence and blending of plies are vital to the properties of composite laminate structures such as the stiffness, buckling load and weight. To maintain structural efficiency, adjacent laminates may have different thicknesses, which is achieved by ply terminations at the laminate boundaries. As a result, ply-drops are inevitable in complex laminate structures like wing skins, and they are vital to the integrity and durability of the laminates due to delamination often occurs around these discontinuities. It is therefore desirable to design the stacking sequence of composite laminate structure under considerations of ply compatibility and manufacturing constraints. In this paper, blending and stacking sequence are considered respectively at global level and local level. At the global level, a global shared-layer blending (GSLB) method is proposed for obtaining the composite laminate structures with maximum global continuity. The GSLB method aims at avoiding delamination at ply-drop location and generating high manufacturable structure with maximum blending property. At the local level, a GSLB based stacking sequence table (SST) technique is adopted to design the stacking sequence of panels with multiple design rules. The uniform distribution requirement is also included to ensure the ply continuity and smooth the load distribution within the structure. Numerical experiment validates the advantages of the proposed method in guaranteeing both manufacturability and mechanical requirements. The reduced computational cost of the numerical experiment shows that the method can be applied efficiently for the stacking sequence design of large-scale composite structures.

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