Engineering method to build the composite structure ply database

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\textbf{A B S T R A C T}

In this paper, a new method to build a composite ply database with engineering design constraints is proposed. This method has two levels: the core stacking sequence design and the whole stacking sequence design. The core stacking sequences are obtained by the full permutation algorithm considering the ply ratio requirement and the dispersion character which characterizes the dispersion of ply angles. The whole stacking sequences are the combinations of the core stacking sequences. By excluding the ply sequences which do not meet the engineering requirements, the final ply database is obtained. One example with the constraints that the total layer number is 100 and the ply ratio is 30:60:10 is presented to validate the method. This method provides a new way to set up the ply database based on the engineering requirements without adopting intelligent optimization algorithms.

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\textbf{Introduction}

Composite materials have been widely used in military and civil aircraft. The ply number of these composite materials varies from dozens to hundreds. The laminate thickness varies from 0.1 mm to 60 mm, or even more. Due to the benefits of low weight, high strength, being corrosion-free and fatigue-resistant, composite materials have been rapidly used in load carrying structures. Unlike metal structures, a variety of design variables must be considered during the composite aircraft structural design and analysis, such as the ply number, the ply angle, the stacking sequence, the symmetry, the characteristics of the first layer and last layer, the manufacture feasibility and so on. In the practical engineering, 0°, 45°, 135° and 90° are the ply angles most widely used. Therefore, there are often 4 choices of ply angle for each ply. With the increase of ply number, the stacking sequence can be very complex. Theoretically, if ply orientation has four options and a ply stacking has 100 plies, there are 100 powers of 4 kinds of stacking sequences. The number of stacking sequences is still large even if the symmetry and other requirements are considered. Hence, it is difficult to decide which stacking sequence is the proper layup for composite materials structure design engineers. If a ply database is formed through manual operation, it’s not practical to complete composite structure ply design for aircraft structures. Therefore, computer programing is introduced to meet the specific requirements of the database automatically.

Ply database must come first when designing composite aircraft structures [1–4]. There have been many researches on the composite stacking sequence optimization. Knowledge-based system or expert system has been introduced to design the composite aircraft structures. A framework of a knowledge-based system was established by Webber and Wu [5–7] to analyse and assess the structural designs. The object of the optimization is weight, the constraints are the failure criteria of local buckling, overall buckling and maximum strain or maximum stress. Kim et al. [8–10] performed stacking sequence optimization using genetic algorithm. The constraints are handled by introducing a new repair strategy. Park et al. [11] used a genetic algorithm with elitist model to optimize the stacking sequence.

In the above studies, the stacking sequence optimization is mostly based on the intelligent optimization algorithms which are time consuming. In practical engineering, we have to think of the efficiency of the methods we use. Moreover, there are many other problems such as robust and fewer options when using intelligent optimization algorithms. In this paper, a method building the ply database based on the practical engineering is proposed without using intelligent optimization algorithms. Compared to the methods above, this method can produce many more stacking sequences that satisfy certain engineering ply rules so that the stacking sequences form a ply database.

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Method to build the ply database

A method of setting up the ply database is proposed based on practical engineering without adopting full permutation algorithms or genetic and neural network algorithms. The core ideas are as follows:

(1) By adopting certain algorithms and satisfying the constraint conditions, the core stacking sequences are produced.
(2) The maximum ply number is obtained based on the core stacking sequences.
(3) By reducing the maximum number of ply stacking sequence, the ply sequence with less plies is formed.
(4) Filter all the stacking sequences according to certain engineering ply rules so that the ply database can be set up.

The engineering ply rules of this method are as follows:

(1) 0°, 45°, 135° and 90° are adopted as the basic ply orientation angles.
(2) Each ply stacking sequence must be symmetrical.
(3) The ply ratio should meet user requirements, for instance, 30/60/10, 40/50/10, 60/30/10, the first number is 0° ply ratio, the second number is 45°/135° ply ratio, the third number is 90° ply ratio.
(4) Each ply ratio must be more than 6%, less than 80%.
(5) Four continuous plies should not have the same orientation.
(6) The plies with the same orientation should be separated as far as possible.
(7) The balance character is defined by users, if the balance character is required, the ply sequences in the ply database which don’t meet the requirement would be removed.
(8) The requirement of balance symmetry. The ply stacking sequence is not only symmetrical, the 45° ply number is also the same as the −45° ply number.

The procedure of this method is as follows:

(1) Form the core stacking table. Usually, the ply number is more than 20 in the practical design. Moreover, the number 20 can satisfy the symmetry and is widely used ply ratio 30/60/10, 40/50/10. As a result, 20 is often taken as the core ply number. In consideration of the symmetry requirement, the actual core ply number is 10. According to the ply ratio, the number of plies of 0°, 45°, 135° and 90° is determined. Then full permutation ply sequences with user determined ply ratio are generated. By removing the ply sequences which have four continuous layers, the core stacking sequence table is formed.

The dispersion character of the ply stacking sequence is defined as follows. If the ply orientation angle is different from the connected upper ply orientation angle, we set the penalty coefficient of the ply as 1, otherwise the penalty coefficient is −1. The sum of the penalty coefficients of each ply forms the layup penalty coefficient. We define the layup penalty coefficient as the dispersion of the stacking sequence. Take the stacking sequence in Table 1 as an example. Add up the penalty coefficients of each ply, the sum of the penalty coefficients is 8. We can evaluate the stacking sequence through the dispersion character. The larger the layup penalty coefficient is, the better the stacking sequence is.

Moreover, there is more than one core ply stacking sequence according to this algorithm. There is also more than one core ply stacking sequence with the same layup penalty coefficient according to this algorithm. This reveals the diversity of the stacking sequences in the ply database. The user can freely decide which core ply sequence will be used to form the maximum ply sequence for the ply database based on the engineering experience.

(2) Form the ply stacking sequences with the maximum ply number. The maximum ply number is based on the design requirement, often the integer multiple of the core ply number. One or several core layups are chosen to form the maximum ply sequence by random combination. We can choose the core ply stacking sequences with larger layup penalty coefficient. For instance, we choose A1, A2, A3, A4 these four core ply stacking sequences in the core ply stacking table. A1 ~ A4 ply stacking sequences, each has 10 plies. If the maximum ply number is 80, the stack sequence can be built as {A1, A3, A4, A2}s or {A2, A3, A1, A2}s, etc. It should be noted that according to the principle of random combination, there are many different ply stacking sequences. The users can determine the sequences of the core ply stacking and the maximum ply number according to their own needs.

(3) Reduce the ply number of each ply stacking sequence to obtain basic ply database. For each ply stacking sequence with the maximum ply number, exclude the 2 frontal layers (the first layer and last layer of the stacking sequence) every time to obtain the next stacking sequence. This operation is continued until the last two layers are left. All the stacking sequences obtained in the operation form the basic ply database.

(4) Check the layup with the engineering requirements. Verify and evaluate all ply stacking by the engineering ply rules such as the symmetry requirement, the ply ratio requirement; the requirement that four continuous layers should not have the same orientation angles, etc.

(5) Obtain the final layup database. Removing the ply stacking that cannot meet all the requirements, the final layup database is then obtained.

The software design of ply database

In order to realize the above ply database design process, we use VBA script language to write the corresponding program. The interface is shown in Fig. 1. The input parameters are: total plies number, the key plies number, the ply percentage. The main part of the procedure is as follows:

```vba
Sub main()
    n_line = 1
    For i = 1 To 100
        core_list(i) = −100
    Next i
    Call read_for_core_list

    Call perm(core_list, 1, 10)

    Worksheets("sheet2").Cells(1, 20) = “the core ply number:”
    Worksheets("sheet2").Cells(2, 20) = n_line - 1
End Sub

Sub read_for_core_list()
    n_ply_0 = Worksheets("sheet1").Cells(7, 2)
    n_ply_45_135 = Worksheets("sheet1").Cells(7, 3)
    n_ply_90 = Worksheets("sheet1").Cells(7, 4)
    act_all_ply = Worksheets("sheet1").Cells(2, 2)
    (continued on next page)
```
all_ply = n_ply_0 + n_ply_45_135 + n_ply_90
For i = 1 To n_ply_0
    core_list(i) = 0
Next i
For i = 1 To n_ply_45_135
    remain = i - 2 * Int(i / 2)
    If remain = 0 Then
        core_list(i + n_ply_0) = 135
        n_ply_135 = n_ply_135 + 1
    Else
        core_list(i + n_ply_0) = 45
        n_ply_45 = n_ply_45 + 1
    End If
Next i
For i = 1 To n_ply_90
    core_list(i + n_ply_45_135 + n_ply_0) = 90
Next i
all_ply = n_ply_0 + n_ply_45_135 + n_ply_90
End Sub
Sub perm(core_list, k As Long, m As Long)
    Dim j As Long
    If (k = m) Then
        If n_line > 300 Then
            Exit Sub
        End If
        Call is_45_135_top_surface(core_list, is_45_135_top_flag)
        Call is_3_ply_connect(core_list, is_3ply_flag)
        Call is_repeat_ply(m, line_is_repeat_flag)
        If (is_3ply_flag = 0 And is_45_135_top_flag = 1 And
            line_is_repeat_flag = 0 Or is_3ply_flag = 0 And
            is_45_135_top_flag = 1 And n_line = 1) Then
            For i = 1 To m
                Worksheets("sheet2").Cells(n_line, i) = core_list(i)
                n_line = n_line + 1
            Next i
        End If
        Else
            For j = k To m
                Call swap(core_list, k, j)
                Call perm(core_list, k + 1, m)
                Call swap(core_list, k, j)
            Next j
        End If
    Else
        For j = k To m
            Call swap(core_list, k, j)
        Next j
    End If
End Sub

Example verification
This section presents an example of building the ply database. The ply database must meet the following user requirements:

1. The total layer number is 100.
2. $0^\circ$, $45^\circ$, $135^\circ$ and $90^\circ$ are adopted as the basic ply orientation angles.

**Table 1**
The layup penalty coefficient.

<table>
<thead>
<tr>
<th>Stacking Sequence</th>
<th>45</th>
<th>135</th>
<th>0</th>
<th>45</th>
<th>135</th>
<th>0</th>
<th>45</th>
<th>135</th>
<th>90</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penalty Coefficient</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

Fig. 1. Interface of the program.
The ply stacking sequences in the database must be symmetrical.

Ply ratio meets 30/60/10.

Each ply ratio must be more than 6%.

Four continuous layers should not have the same orientation angles.

| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 135 | 45 | 0 | 45 | 135 | 45 | 90 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 135 | 45 | 90 | 45 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |

Fig. 2. Part of the core layup option table.

| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 135 | 0 | 45 | 135 | 45 | 90 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |
| 45 | 135 | 0 | 45 | 0 | 135 | 0 | 45 | 135 | 0 | 135 | 45 | 90 | 0 | 0 | 45 | 135 | 0 | 135 | 0 | 10 |

Fig. 3. Basic ply database.

(3) The ply stacking sequences in the database must be symmetrical.

(4) Ply ratio meets 30/60/10.

(5) Each ply ratio must be more than 6%.

(6) Four continuous layers should not have the same orientation angles.
(7) The ply with the same orientation spreads as far as possible.

(8) The 45° ply number is also the same as the −45° ply number.

The detailed realization process is as follows:

1. Enter the appropriate parameters in the interface in Fig. 1.

2. The core ply stacking table is formed as in Fig. 2. There are many ply stacking sequences, the final column shows the layup penalty coefficients.

3. Form the basic layup database. We choose the first 5 core ply stacking sequences to form the basic layup database as in Fig. 3. The symmetric part of the sequences is not shown.

Fig. 4. The evaluation results of basic ply database.

Fig. 5. The final ply database.
(4) Evaluate the ply stacking sequences. We value the ply stacking sequences in the basic layup database by the user requirements list above. The result is shown in Fig. 4.

(5) Remove the ply stacking sequences which do not meet all the requirements, the final layup database is obtained. The ply stacking sequences in the ply database can satisfy all the user requirements which can be used in the design and analysis of composite aircraft structure. The final layup database is presented in Fig. 5.

Conclusion

In this paper, a new method to set up a composite material ply database is proposed. This method has two levels: the first level is the core stacking sequence design, the second level is the total stacking sequence design. The dispersion character is introduced to characterize the dispersion of ply angles and evaluate the stacking sequences. This method provides a new practical way to obtain the ply stacking sequences meeting the engineering requirement in the layer database design. The ply database provides a variety of options of ply stacking sequences which will be used in the following composite aircraft structures design stage.

References