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From stacking sequences to ply layouts: An algorithm to design manufacturable composite structures

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ABSTRACT

The problem of computing the ply lay-outs of a composite structure from the definition of the stacking sequences of the zones is studied in this paper. These stacking sequences result from the design of the composite structure and they are considered to be admissible with respect to standard composite design and manufacturing rules. This paper shows that the definition of blended stacking sequences does not necessarily lead to a possible solution for the ply layouts. Therefore, the design process of a composite structure must include a further step after computing the stacking sequences which is to compute the ply layouts. The paper presents an algorithm to compute a ply layout solution for a given set of stacking sequences. Using a backtracking approach, it efficiently checks all the possible ply layout combinations to find a solution. Some numerical experiments are presented to study the mapping between stacking sequences and ply layouts and the existence of a ply layout solution.

1. Introduction

A common practice during the design of a composite structure is the use of an automatic tool to generate the stacking sequences and ply layouts. Such a tool can be of great help for the design engineer when dealing with the design and manufacturing rules given the combinatorial nature of the problem. It easily provides with all the possible choices for the stacking sequences and their corresponding ply layouts in a reduced computational time. This feature increases the efficiency of the final design. The automatic tool can also be integrated into an optimization procedure. In this case, the automatic tool provides a detailed description of the composite structure. It computes the stacking sequences and the ply layouts, which correspond to the high level optimization design variables.

This paper addresses the problem of generating the ply layouts of a composite structure given the stacking sequences of its zones and following a set of manufacturing rules. This problem arises in many situations. Suppose that a optimal design computed by an optimization procedure is found not satisfactory by the design engineer. If the design is enhanced by doing some changes to the stacking sequences, the ply layouts have to be recomputed according to the new stacking sequences.

This problem also arises when performing a stacking sequence optimization without considering the blending constraint. It is the case of the continuous variables approach and the permutation genetic algorithms. Such approaches, presented in [5,13–15], compute the stacking sequences independently from each others, and they only consider the design rules applied individually to the stacking sequences. Therefore, the ply layouts have to be computed after the stacking sequences.

There are two existing methods, in the literature, for computing the ply layouts. However, they admit some restrictions over the ply layouts which limit the set of possible choices. The optimization methods based on the shared layer technique, presented in [1–4], compute the ply layouts before computing the stacking sequences. This method imposes that the plies constituting the thinnest zone of the structure are shared by all the zones.

A set of optimization methods have been developed based on a stacking sequence guide (see [6–12,16,18]). In the case of these methods, the mapping between stacking sequences and ply layouts is straight forward and there is no need for a specific algorithm to convert stacking sequences into ply layouts. However, the use of a stacking sequence guide brings a limitation to the possible choices for the stacking sequences. The stacking sequence guide associates one stacking sequence to each zone thickness. Thus, all the stacking sequences with the same number of plies are identical.

An algorithm for generating admissible stacking sequences with respect to the design and manufacturing rules, and not restricted

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to a stacking sequence guide, has been presented in [17]. This paper presents another algorithm which computes the ply layouts given the stacking sequences of the zones of a composite structure. Like the previous algorithm, this one is also formulated as a constraint satisfaction programming problem and it is solved using a backtracking procedure. It shows that the definition of blended stacking sequences does not necessarily lead to a possible solution for the ply layouts. Some numerical experiments are presented to study the mapping between stacking sequences and ply layouts and the existence of a ply layout solution.

2. The design and manufacturing rules

In order to have a good mechanical behavior of the composite structure, some design rules are adopted by the composite manufacturers. These rules represent a rough approximation for reducing the risk of failure of the structure. In the following, some examples of design rules are cited.

- The orientation in each ply must be chosen such that two consecutive plies do not have a gap in the orientation equal to 90°. Thus, $(0, 90)$ and $(-45, 45)$ cannot be two consecutive plies.
- Maximum four consecutive plies can have the same orientation.
- Only symmetric sequences are acceptable.
- Uniform distribution of 0 and 90 plies through the sequence: these orientations are not gathered in one part of the sequence. For example the sequence $(0, 0, 0, 0, 45, 90, -45)$ is not admissible because the zeros are grouped together and they are not uniformly distributed over the sequence.
- A maximum of four consecutive interleaved plies: a maximum of four consecutive plies can be dropped to obtain a subsequence. For example, the two blended sequences which have the ply numbers $(1, 2, 3, 4, 5, 6, 7, 8)$ and $(1, 7, 8)$ are not admissible because five consecutive plies are dropped $(2 - 6)$
- Symmetrical except for odd number of plies in the -45 and 45 directions: a dissymmetry in the center of the laminate is allowed. Asymmetric ± 45 layers in the center of the laminate are separated at maximum by one layer. It is not possible to have a symmetric sequence with an odd number of plies in ± 45, thus a dissymmetry is allowed in the middle of the sequence. For example, consider a sequence with (3, 2, 3, 2) plies of $(-45, 0, 45, 90)$. The only possible way to generate a sequence is like this: $(-45, 0, 45, 90, -45|45, 90, 45, 0, -45)$. It is a symmetric sequence except in the middle where we have the $-45|45$ dissymmetry. Another allowed dissymmetry in the middle is $-45, 0, 45$ and $-45, 90, 45$. Note that if this rule is considered with the symmetry rule and the fixed number of plies per orientation, the number of 0 or 90 must be odd otherwise the symmetry rule is violated.
- In the context of a preliminary design of a structure, a fixed number of plies of each orientation is defined in each panel. These numbers of plies are the results of optimal values of the design variables.

In addition to these design rules, the blending manufacturing rule has to be considered. This rule states that if two zones A and B are connected together and A has more plies than B, then the plies of B are a subset of the ones of A. This rule prevents from having bolt joints between the connected zones.

3. The problem formulation

A ply layout gives a physical description of the ply. It defines the fiber orientation of the ply, its position in the stacking sequence and its covering zones. Considering the layouts of all the plies, the manufacturer must be able to assemble them and produce the desired composite structure. Each ply in the composite structure has a unique number called id. From the sequence of ids one can deduce the sequence of orientations in a specific zone or the covering zones of each ply. Fig. 1 gives an example of a structure divided into 3×3 zones and Fig. 2 gives an example of four ply layouts. In this example, zones $(2, 5, 6, 9)$ have the stacking sequence $(45, 0, 90, -45)$, zones $(7, 8)$ have the orientation sequence $(45, 0, -45)$, zones $(1, 3)$ have the stacking sequence $(45, 90, -45)$ and zone 4 has the stacking sequence $(45, -45)$.

The paper addresses the problem of computing the ply layouts given the sequences of fiber orientations of each zone. In the following, we start by giving a formulation this problem in terms of Constraint satisfaction programming (CSP).

3.1. The variables

The stacking sequences of the zones are represented by the nodes of a connected graph. If two zones are connected, then the corresponding two nodes are linked by an edge (see Fig. 1). Let n^i be the total number of plies in zone i, x^i be the sequence of ply ids in this zone, $s(x^i)$ the sequence of fiber orientations of this zone. x^i is a vector of n^i unique integers. Let s^i be the prescribed sequence of ply orientations of this zone. The computed ply layouts must match this sequence.

3.2. The ply drop-offs

Let i and j be two connected zones with $n^i \geqslant n^j$. These two zones are blended together. Therefore, x^j is a subsequence of x^i. The plies of zone j are present in zone i and some plies are dropped when moving from zone i to j. The application $b^{i,j}$ which converts x^i into x^j is parametrized by binary vector of size n^i and it has n^j ones: a zero represents a drooped ply and a one represents a kept ply. We denote by $\mathcal{B}^{i,j}$ the set of $b^{i,j}$'s. Each element of this set defines a possible choice for the ply drop-offs between zones i and j.

We define the application $x^j = b^{i,j}x^i$ in the case of $n^i < n^j$ as follows. Same as in the previous case, a binary vector defines the ply drop-offs between zones i and j. One corresponds to a common ply for both zones i and j, and zero corresponds to a ply which does not exist in zone i. Such plies are given new ids. In the previous example, $x^2 = (1, 2, 3, 4), x^1 = \{1, 3, 4\}$ and there is one binary vector defining the ply drop-offs between zones 2 and 1 which is $(1, 0, 1, 1)$.

3.3. The constraints

The constraints are defined by the edge connecting the variables. Each edge between nodes i and j defines the following constraint. x^j and x^i are blended, and the corresponding orientation sequences must match the prescribed ones:

$$\begin{cases} x^j = b^{i,j}(x^i), \text{ with } b^{i,j} \in \mathcal{B}^{i,j} \\ s(x^i) = s^i, \\ s(x^j) = s^j. \end{cases} \tag{1}$$

The CSP problem consists in finding the x^j's, the ply ids of each stacking sequence, such that all the constraints are satisfied.

4. Comparison with other methods

In this section, we show the advantages of the CSP method over the sequence guide method and the shared layer method. Consider a structure with four aligned zones, A, B, C and D with respectively