Composite Optimization - Ply Drop-Rate Constraints for Concept and Detailed Design

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Summary Composite material offers unmatched design and manufacturing flexibility. The increased complexity also presents new challenges for engineering design and manufacturing. In recently years the authors have developed a comprehensive optimization process for composite laminate structures [2][3]. This process is implemented in the commercial software OptiStruct and has gained increasing usage on design of next generation airliners at major aerospace OEMs. This paper addresses ply thickness blending as an additional requirement arisen from such applications.

COMPOSITE DESIGN CONCEPT OPTIMIZATION

Design concept of composite laminate structures involves definition of thickness and shape of plies of different fibre orientations. Build-up of thin plies of different shapes can produce continuously varying laminate thickness. Combined with variation of fire orientation for each ply patch, laminate properties can be tailored almost continuously throughout the structure. When ply shape definition is given, Stegmann and Lund [1] proposed a SIMP based approach for material/fibre-orientation selection. For general thickness blended laminate structures, Zhou *et al.* [2][3] introduced a free-size approach where each fibre orientation is represented by a super-ply and thickness of each super-ply is allowed to vary element wise. This results in a near continuously varying thickness field of each fibre orientation. Discrete interpretation of the thickness landscape creates ply shape as well as corresponding thickness design proposals. Note that manufacturing constraints are needed during this concept generation phase to address requirements such as limiting consecutive plies of same orientation. The optimization problem can be formulated as follows:

$$\begin{aligned} &\text{Minimize} \quad f(\boldsymbol{x}) \\ &\text{Subject to} \quad g_j(\boldsymbol{x}) - g_j^U \le 0, \quad j = 1,\dots, M \\ &\qquad x_{ik}^L \le x_{ik} \le x_{ik}^U, \quad i = 1,\dots, Np, k = 1,\dots, NE \end{aligned} \tag{1}$$

Where NE is the number of elements and Np the number of super-plies; x_{ik} is the thickness of the i-th super-ply of the k-th element. In addition, manufacturing constraints such as total thickness and ply percentage constraints are considered to addressing manufacturing and design rules:

$$\begin{aligned} &\text{Total thickness}: T_k^L \le \sum_{i=1}^{Np} x_{ik} \le T_k^U, \quad k = 1,\dots, NE \\ &\text{Ply percentage}: P_j^L \le \frac{x_{jk}}{\sum_{i=1}^{Np} x_{ik}} \le P_j^U, \quad j = 1,\dots, Np, k = 1,\dots, NE \end{aligned} \tag{2}$$

Thickness blending is address in this paper as another very important design requirement from aerospace OEMs. Gradual thickness change can be achieved by managing ply shape changes in the laminate build-up. For Free-Sizing optimization phase this requirement can be represented by the following thickness slope constraint:

$$\text{Ply drop rate}: |x_{ij} - x_{ik}| \le \delta \cdot dist(j,k), \tag{3}$$

where x_{ij} and x_{ik} denote adjacent elements j and k of i-th super-ply, δ represents ply thickness dropping rate over one in-plane length unit, $dist(j, k)$ the distance between element j and k. As shown in [4] in the context of density slope control, the constraints in Eq.(3) can be addressed efficiently by adjusting variable move limits during optimization iterations.

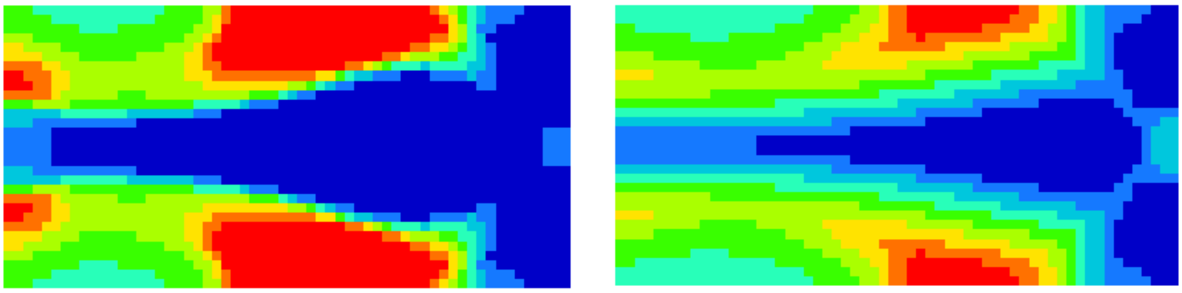

Fig.1 Cantilever plate - 0° Ply thickness with (right) and without (left) ply drop-rate constraint

Fig.1 shows the effect of ply drop-rate control with a simple cantilever plate with 0^o, $\underline{+}45^o$,90^o plies. The plate is supported on the right edge and a vertical point load is applied at the center of the left edge. The thickness contour of 0^o super-ply shows that ply drop-rate constraint results in a gradual thickness change as expected.

PLY-PATCH SIZING AND PLY STACKING OPTIMINZATION

Thickness field of a super-ply illustrated in Fig.1 is interpreted into ply patches of different shapes by discrete slices of the thickness landscape. The resulting ply patches are stacked in alternating sequence in terms fibre orientations, resulting in a FEA laminate model with increased stacking effect representation. Sizing optimization is carried out on thickness of each ply patch, typically at discrete increments representing basic manufacturing ply thickness. Ply drop-rate constraint during this design phase are defined by thickness upper bound as required by design rules of the OEM. In addition, total thickness drop-rate (blending) control is often required. All thickness transition boundaries need to be treated with thickness drop-rate constraint. other manufacturing constraints such as percentage of fibre orientation remain whilst all detailed behaviour constraints (e.g., failure, buckling and displacements etc.) are considered. Since the number of design variables is highly reduced, there is no difficulty for optimization algorithm to handle such constraints.

In the final phase of the three-phase process detailed stacking sequence is optimized satisfying all manufacturing and performance constraints. At this stage, ply drop-rate constraints became explicit control of number of plies allowed to drop off. This is considered alongside other detailed stacking rules such as limiting consecutive plies of same orientation. The final outcome of this process contains all ply-book details of the design. The only design refinement to follow is to smooth stair shaped representation of element-based ply boundaries.

Fig.2 show application of the three-phase optimization process on a wide-body wing cover. Ply drop-rate control leads to a smooth transition of thickness of the wing cover.

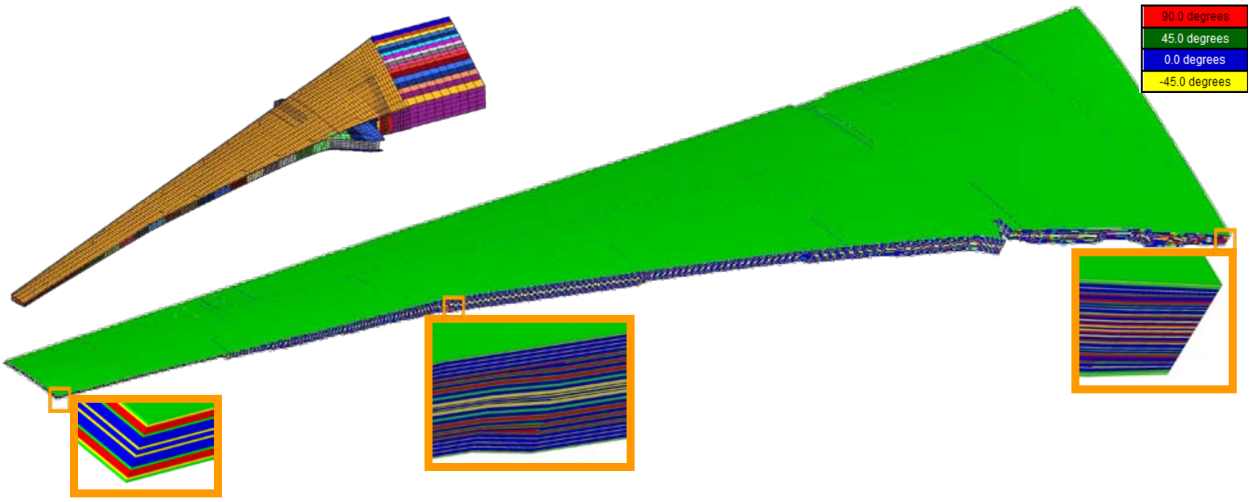

Fig.2 Ply drop-rate controlled top cover of composite wing of a wide-body airliner

CONCLUSIONS

A comprehensive methodology for composite design has been developed by the authors in recent years. Available within the commercial software OptiStruct it has seen quick adoption and early successes in aerospace, auto-racing and other industries. This paper addresses a more recent enhancement in ply and laminate thickness drop-rate control. Ongoing research is driven by needs for more accurate behavior target during concept optimization phase. Considering ply failure constraints during Free-Sizing phase is challenging due to very large number of design variables involved. Also there is increasing needs to address new manufacturing process that allows continuous fibre orientation change with flexible fibre filament placement.

References

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