Optimisation of Variable Stiffness Laminates

Background

Composite laminates are increasingly being used in the aerospace industry; the first composite-dominated airplanes are being built (e.g. A400M, B787). Composite materials are used because of their high stiffness-to-weight and strength-to-weight ratio. Traditionally, single plies have straight fibres, however, fibre placement machines have evolved and now it is possible to lay down fibres in any desired path, which has the promise to reduce the structural weight even further. Laminates with curbed fibres are called variable stiffness laminates; laminates with straight fibres are called constant stiffness laminates. Over the past years a lot of research has been done to optimise the performance of composite structures. One of the proposed solutions was letting the fibre angle vary linearly. This means the search space was limited, leading to suboptimal laminates. Another approach did not limit themselves to linearly varying angles, but the manufacturability was neglected, leading to large improvements on paper, but the design could not be manufactured. This research focuses on searching in the complete design space, while ensuring the final design can be built. To achieve this the complete design space is taken into account and a lot of constraints are posed. As a basis the three-step optimisation approach already developed at TU Delft will be used. Improvements will be made in each step, with the focus being on the fibre angle optimisation.

Combining Lamination Parameter and topology optimisation

In the first step, the optimal lamination parameter distribution is found. This will be combined with topology optimisation such that both the place where material is used and the properties of the material are optimised at the same time. Both implicit and explicit penalisation is used to drive the fictitious density to either zero, indicating a void, or one, meaning the material is present. Results showed that explicit penalisation leads to densities closer to zero or one without adding much computational time with respect to the implicit penalisation method.

An extra step is added to the three-step framework because the contours of the structure have to be found before the fibre angles and paths are determined. An example of this four-step approach, applied to a cantilever beam clamped in on the left and loaded downward in the right bottom, can be seen at the bottom of the page. In this case the topology does not change when topology and lamination parameter optimisation are combined. However, it was shown that for an asymmetric load case, the combined topology and lamination parameter optimisation could find an almost symmetric topology. If the topology was optimised using a quasi-isotropic material, the topology was asymmetric. Furthermore, when the material was only optimised after the optimal topology was found, the stiffness was 5% lower when topology and lamination parameters were optimised at the same time.

Local steering constraints

In the third step of the optimisation approach the fibre angles are found. A crucial point for manufacturability and performance of the structure is the steering of each tow. The maximum steering is determined by the wrinkling of the tows and the capabilities of the machine. If the steering is locally too high, the part cannot be built. In the current method the global steering was constrained, meaning the average norm of the gradient of the fibre angles was constrained. Since the average is constrained, the maximum can be much higher, meaning one has no control about the maximum. Hence, the constraint has to be (much) tighter than the actual maximal steering, in order to avoid this the norm of the gradient of each element is constrained. This leads to a lot of constraints, but now the steering constraint is enforced on each element. The constraint can be the maximal machine/material can handle. The global constraint can still be used to avoid too many gaps or overlaps occurring.

In the top right, the local steering in each element of a structure optimised for the first two buckling loads is shown. The top one shows what happens when a global constraint of 5 is used: the local maximum (36) is much higher than the constraint, while at other places the steering is much lower. In the bottom picture a local steering constraint of 16 is used. Hence the maximum steering is much lower than when using global constraints, but nevertheless the performance is increased with 5% of the quasi-isotropic design with respect to the optimum found using the global constraint.

Example of variable stiffness composites

Step 1: find the optimal topology and lamination parameter distribution

Theoretical optimum, no information about the fibre angles

Step 2: find the contours of the optimal structure

Refining mesh, finding contour and smoothing contour

Step 3: find the optimal fibre angle distribution

Local steering constraints implemented, only first iteration based on step 1

Step 4: find the optimal fibre paths for manufacturing

Fibre paths to follow the fibre angle distribution as closely as possible

Future work

The combination of lamination parameters and topology optimisation will be further developed by having a topology optimisation for each ply, adding the possibility to have ply drops in the structure. A minimal distance between ply drops will be implemented to keep manufacturability of the final result. To ensure manufacturability, some more constraints will be implemented: the (continuous version of the) 10% rule and a minimal fibre angle change between adjacent layers will be implemented. Furthermore, the thermal stresses due to curing, which usually have a positive effect on the behaviour will be implemented.

Publications


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