The high strength-to-weight and stiffness-to-weight ratio of composites are due to the build-up of the material: it consists of very strong fibres that are embedded in a matrix. These fibres are very strong in tension while the matrix takes up most of the compression load, comparable to reinforced concrete but on the micro-level. A combination of fibres and matrix is called a ply and is very strong in the direction of the fibres, but weaker in the other directions. By stacking multiple plies with the fibres in different directions on top of each other, one gets a composite laminate. A graphical representation of such a laminate can be seen in Figure 1. These composites are designed to be relatively strong in all directions, and particularly strong in the direction of the largest loads. By changing the fibre angle orientation one can tailor the strength and stiffness of the composite in different directions. The orientations of the fibres in the different plies are written down in a so-called stacking sequence.

VARIABLE STIFFNESS COMPOSITES

Building composite materials used to be manual labour, which led to extremely high costs and limited accuracy. However, over the past years fibre placement machines were developed to automate the process and nowadays these fibre placement machines have evolved far enough that they can lay down fibres in any direction, not just straight. This opens up a lot of new possibilities to tailor the material properties: the fibre direction can now change inside a layer and thus also the material properties (strength, stiffness etc.) can change from one point to the next. Hence, these composites are called variable stiffness composites.

Variable stiffness composites give a lot of new possibilities, so much even that it is no longer possible to find the optimal fibre angle distribution without an optimisation algorithm. Such an algorithm has been developed at TU Delft and it uses a three-step approach (Ijsselmuiden, 2011). In the first step the material properties are represented by lamination parameters. The advantage is that only four lamination parameters are needed to define the material properties; when the composite has a symmetric stacking sequence with respect to the mid-plane of the laminate, only two lamination parameters are needed. In this step, the theoretical optimal performance (e.g., buckling load) is found, but the lamination parameters give no information about the stacking sequence. This stacking sequence is found at all nodes of the finite element model in the second step of the optimisation algorithm. The difference between the angles in adjacent nodes is constrained to be sure the composite can be made by a fibre placement machine: these machines cannot make very sharp turns. Due to this constraint the lamination parameters cannot be matched exactly at each point and the performance decreases a bit. In the third step the actual fibre paths are found. This is done to match the fibre angles at the nodes as closely as possible.

Weight reduction has been a driving factor in aerospace engineering for a long time. Recently, the first composite-dominated airplanes (e.g., A-380, B-787) have been taken into use. Composites have replaced aluminium because of their higher strength-to-weight and stiffness-to-weight ratio. Currently, research is ongoing on variable stiffness composites which have the promise to further reduce the weight of composites.

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A new optimisation approach for future composite materials
TOPOLOGY OPTIMISATION
A popular optimisation algorithm for isotropic materials is topology optimisation. This approach optimises the material distribution by giving each node of the finite element model a fictitious density. If this density is zero, there is a void; if it is one, the material is present at that node. A maximum allowed volume of the structure is specified and then the stiffness, strength or buckling load of a structure under a certain load can be optimised.

By combining topology optimisation with the first step of the variable stiffness optimisation approach, both the material distribution and material properties are optimised at the same time. The result of this optimisation consists of a lamination parameter distribution and a material presence distribution, as can be seen in the left of Figure 2. Before the fibre angles and paths can be determined, first the contour of the optimal structure is determined. This is necessary because the elements used are usually either triangular or rectangular and thus the edges are wavy. By linearly interpolating the density distribution and smoothing the edges found in that way, a smooth contour line is found. Once the contour is determined, the fibre angles and paths are determined in the same way as was done in the variable stiffness optimisation. When optimising the stiffness of a cantilever beam clamped in on the left, with a downward force on the right, the optimal topology and fibre paths can be seen in Figure 2. This gives a 58% increase with respect to a quasi-isotropic lay-up.

POSSIBLE IMPROVEMENTS
The results obtained using this approach are promising, but improvements can still be made. One of these improvements is that the maximum curvature mentioned above is currently the global curvature, which means the curvature can locally be too high leading to a laminate that cannot be built. Furthermore, what has been referred to as fibre paths so far is in fact only a good impression of what the fibre paths will look like.

A typical fibre placement machine lays down bands of 6 to 50mm while the example shown is 300mm wide. Furthermore, the distance between fibre paths is not constant anymore and the bands laid down only differ by about 6mm. This implies one will have to make a choice: place fibres on top of each other, or leave parts ‘empty’. The first case causes a variable thickness solution as can be seen in Figure 3; the second case leads to regions with only matrix material and no fibres. In the aviation industry the second case, with a constant thickness, is generally preferred to keep the aerodynamic shape of the structure.

As a final improvement it should be possible to also change the thickness of the laminate: by dropping certain plies, the material properties will change, even if the fibre angle inside a ply stays constant. By having both varying fibre angles and variable thickness it is expected that even larger weight savings can be accomplished. By changing both fibre angle and thickness, the potential change in stiffness will also be larger from one point to the next: only one or two plies can be dropped at once, and the fibre angle can not change a lot locally, but by combining both, the stiffness variation can be large. The final goal is to design a complete wing panel, about 2m by 3m in size, with the fibre paths optimised, change in thickness and reduced number of stiffeners compared to current designs. An example of a current wing panel can be seen in Figure 4. Compared to the current state of the art wings, this will reduce the structural weight and, since less stiffeners will have to be used, the production time and cost will also be reduced.

Some of the possible improvements will be made by TU Delft, but this work is also supported by the European Seventh Framework Program, and is part of the CANAL project (CrAting Non-conventionAl Laminates) where also commercial companies, aerospace research institutes and other universities are involved.

Concluding, even though a lot of improvements are still possible, it is already clear variable stiffness laminates can reduce the structural weight of aerospace structures.

If you have further ideas or want to contribute to this research as a graduate student, contact the author for further information.

References