LAYUP OPTIMIZATION AND WAYS TO IMPROVE THE MANUFACTURABILITY OF COUPLED COMPOSITES

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ABSTRACT

This paper introduces a comprehensive design process of coupled composite layups. Optimizing the layup for a morphing race car diffusor is the example case study. Analytical optimization is followed by numerical simulations and validation by physical testing. As a first step, the analytical optimization tool (written in MATLAB) finds the optimal layup for the desired coupled mechanical behaviour (e.g. twisting in response to bending moment) by calculating and comparing the magnitude of the coupling terms of each layup permutation based on the classical laminate theory (CLT). The realistic boundary conditions and loads are simulated numerically with the use of finite element modelling. The autoclave-prepreg manufactured specimens are then tested physically on universal test machines to validate modelling results.

The optimized coupling behaviour was found to be significant enough to promise notable aerodynamic advantage over the traditional diffusor. The optimization process proved to be useful. It is possible to use this process to optimize the layup for a wide variety of different components with coupling behaviour.

Furthermore, this paper presents possible solutions to mitigate thermally induced warping of coupled composites with non-symmetric layups. Laminating on tools with excessive curvatures to counterweigh thermal warpage during manufacturing, or designing composites with hybrid layups in terms of the ply materials are proposed.

1 INTRODUCTION

Composite materials are best known for and most often used because of their outstanding specific mechanical properties. Apart from the strength and stiffness of the reinforcements, the two keywords here are orientation and anisotropy. It is possible, however, to exploit the direction dependent mechanical behaviour of composites for another use: designing coupled (morphing) structures.

Morphing structures are capable of deformations that are different from the mode of actuation. A conventional deformation would be elongation in response to tensile force or bending in response to bending moment, etc. A non-conventional deformation can be twisting in response to bending moment or even bending in response to light exposure, for instance. A wide variety of morphing concepts exist in the literature. Electrically actuated shape changes are amongst the most researched concepts. Most of these approaches use either piezoelectric materials [1], electromotors [2], dielectric elastomers [3], or conjugated polymers [4] as actuators. The greatest advantage of electroactuated systems is the accurate controllability of deformations. Other morphing systems are actuated by heat (e.g. shape memory polymers [5] and alloys [6]), light [7], pressure [8] or chemicals [9]. Each and every one of the concepts have their advantages and disadvantages. However, most of them rely on external, "active" actuation in order to work. Composites, on the other hand, can display non-conventional deformations “passively”, without the need of external stimuli other than the operational loads that are naturally acting on them. This passive shape adaptation to operational loads can be exploited to produce more efficient aerodynamic parts, for instance (e.g. bend-twist wind turbine blades [10] or extension-twist rotor blades [11]).

The classical laminate theory (CLT) establishes the relationship between the six fundamental loads and six modes of deformation in the form of a 6x6 (so called ABD) matrix, for a given laminate. This analytical model offers a simple way to evaluate the coupling behaviour of a composite, by quantifying the effect of any load on any deformation. Amongst others, extension-shear [12], extension-twist [13] and bend-twist [14] coupling (morphing) can be evaluated this way. However, by its nature, the analytical method is limited, as it cannot handle complex shapes or boundary conditions. Here, numerical simulations can be of help before the component with the optimized layup goes into production.

Beside layup optimization, the mitigation of thermal warping is a great challenge. Coupled composites often have non-symmetric layups. This means that the out-of-plane stresses in response to thermal loads are not balanced and the laminate warps during the manufacturing process. This is an unwanted deformation that needs to be mitigated. Therefore, there are two main goals of this paper. Firstly, to propose a comprehensive layup design process of coupled (morphing) composites. And secondly, to propose possible solutions to the thermally induced warping of these composites.

2 LAYUP OPTIMIZATION OF A COUPLED COMPOSITE

This section introduces a case study where a morphing composite component is optimized analytically, simulated numerically, and finally manufactured and tested. The modelled and measured results are then compared and the accuracy of the analytical and numerical methods are evaluated.

2.1 The component of optimized layup

The chosen component is a race car diffusor. This component is used to produce downforce and due to aerodynamic reasons it works better if its edges along the two sides of the car move closer to the ground at greater speeds. The aerodynamic load on the component mostly tries to bend it, therefore for this case study, we assume simple bending moment as the load. The goal is to achieve maximum deflection at the edges in the transverse direction. This can be achieved by two concepts. The composite part can bend transversely in response to applied bending moment. Or alternatively, the component can be split in half along the length of the car, and twist in response to applied bending moment. Either way, the desired deflection can be achieved. The question is: which concept is better? To find out, we ran two optimization studies: one for maximum transverse bending and one for maximum twisting in response to applied bending moment.

2.2 Analytical optimization

The analytical optimization of the layup was based on CLT and was carried out in MATLAB. We optimized a 4-ply carbon-epoxy (E_1=183.3 GPa, E_2=9.74 GPa, G_{12}=4.12 GPa, ν_{12}=0.3, ply thickness=0.13 mm) laminate by changing the orientation of its plies by 7.5° at a time and calculating the inverse ABD matrix for each of the more than 300,000 layup permutations. In our case, optimal coupled behaviour was maximal coupled behaviour. Therefore, we were looking for maximal values when comparing the inverse ABD matrices of the layups. $D_{12}*$ had to be maximized for transverse bending, and $D_{16}*$ for twisting (1).

$$\begin{bmatrix} \varepsilon^0{}_{xx} \\ \varepsilon^0{}_{yy} \\ \varepsilon^0{}_{xy} \\ \kappa_{xx} \\ \kappa_{yy} \\ \kappa_{xy} \end{bmatrix} = \begin{bmatrix} A_{11}* & A_{12}* & A_{16}* & B_{11}* & B_{12}* & B_{16}* \\ A_{12}* & A_{22}* & A_{26}* & B_{12}* & B_{22}* & B_{26}* \\ A_{16}* & A_{26}* & A_{66}* & B_{16}* & B_{26}* & B_{66}* \\ B_{11}* & B_{12}* & B_{16}* & D_{11}* & D_{12}* & D_{16}* \\ B_{12}* & B_{22}* & B_{26}* & D_{12}* & D_{22}* & D_{26}* \\ B_{16}* & B_{26}* & B_{66}* & D_{16}* & D_{26}* & D_{66}* \end{bmatrix} \begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \\ M_{xx} \\ M_{yy} \\ M_{xy} \end{bmatrix} \tag{1}$$

We found that the [142.5°/97.5°]$_s$ layup gave maximal twist and the [67.5°/30°/60°/22.5°] layup gave maximal transverse bending in response to a given bending moment. When comparing the achievable deflection of the two concepts, twisting promised significantly larger deflections to the same load compared to the transversely bending laminate, therefore we chose the twisting concept and carried out all the following steps for that laminate only.

2.3 Numerical simulation

For the numerical simulations we used ANSYS Workbench 18.2. A 180 mm x 180 mm plate of the optimized bend-twist composite was fixed at one edge and loaded with a loading pin (10 mm diameter) at the centre of the opposite edge (Figure 1). This is a more realistic boundary condition and loading than what the analytical model can handle. The parameters were chosen so that later we would be able to manufacture and test a composite plate with the same setup. In order to get reliable data, we ran a mesh convergence analysis and the optimal number of elements (SHELL181) was found to be 8100 with good convergence.

Figure 1 illustrates the total deformation of the plate in response to bending load. The twisting of the plate is obvious from the colour distribution.

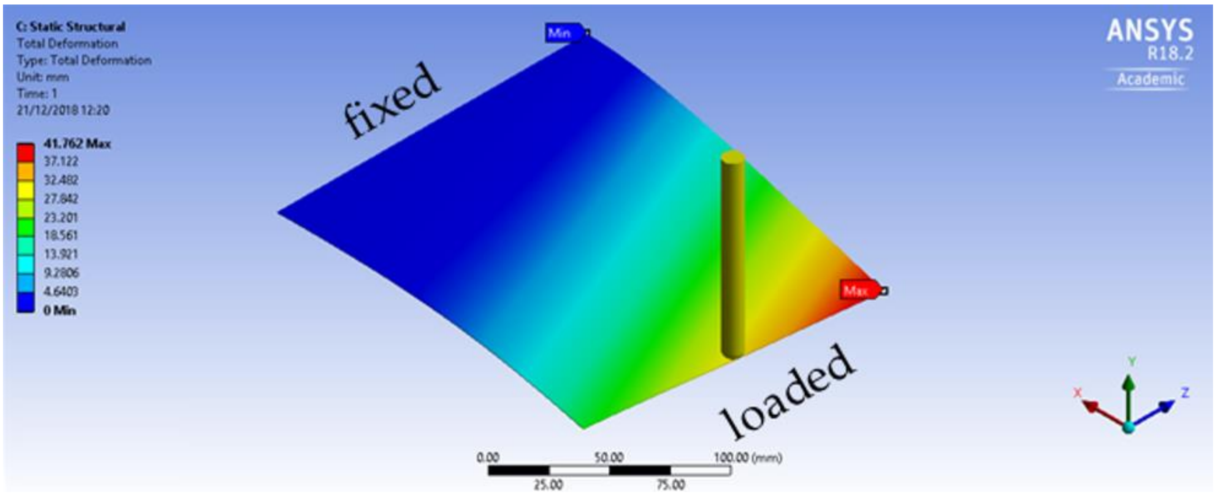

Figure 1 Finite element simulation of a cantilever bend-twist coupled composite under bending load. Total deformation plotted.

2.4 Manufacturing and testing

We manufactured the laminate with autoclave-prepreg technology to get the best possible quality. The 180 mm x 190 mm laminate had the extra 10 mm length for clamping.

Figure 2 illustrates the test setup. Bending was performed with a crosshead speed of 30 mm/min while the positions of markers along the loaded edge were recorded with a video extensometer, up to 30 mm mid-point deflection.

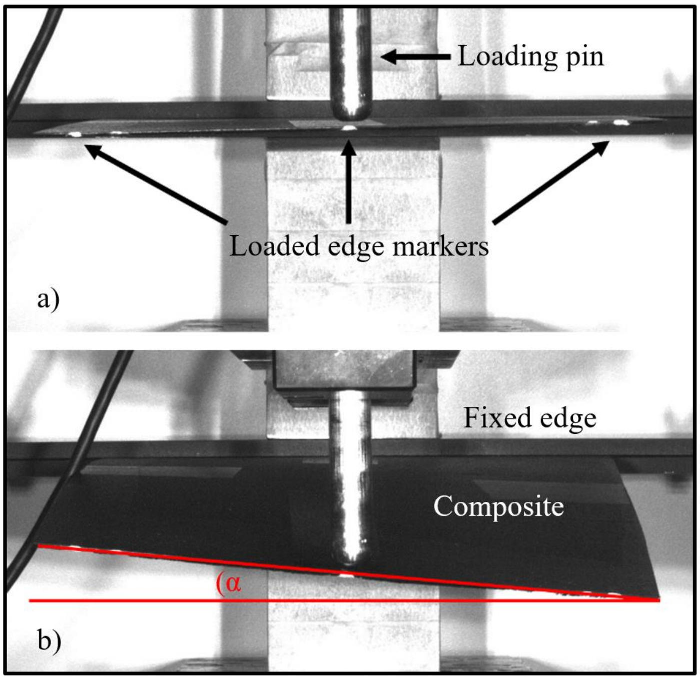

Figure 2 Bend-twist composite cantilever test setup. a) unloaded plate b) loaded plate.

2.5 Modelling and experimental results for bend-twist coupling

Figure 3 illustrates the comparison of the analytical, numerical and experimental results. For best comparability, the rotation of the loaded edge was calculated and illustrated as a function of the mid-point deflection, up to 30 mm mid-point deflection.

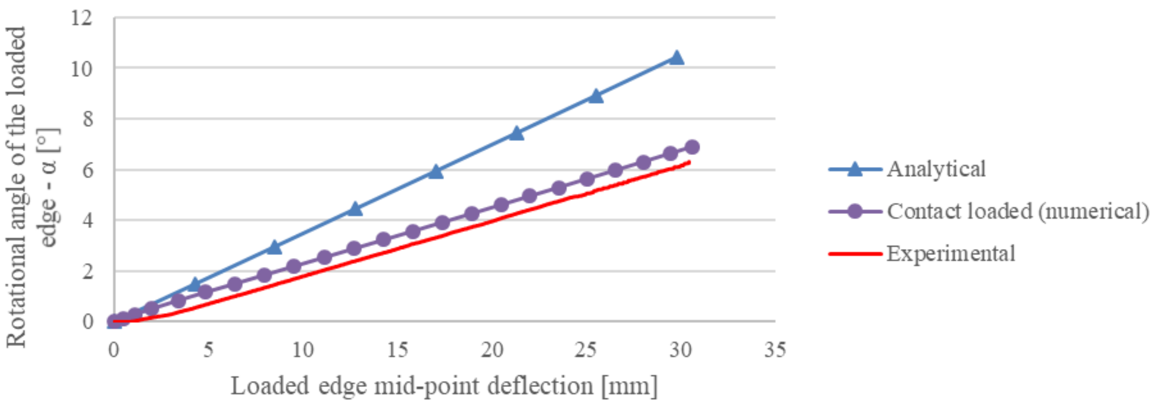

Figure 3 Analytical, numerical and experimental result comparison of the cantilever bending of a bend-twist composite plate. Rotational angle of the loaded edge as a function of the mid-point deflection of the loaded edge.

At 30 mm mid-point deflection, the bend-twist coupled plate twisted 6.2° during the experiment. The analytical model predicted 10.5°. The explanation for the difference can be found in the simplifications of the analytical model. The plane stress state and other assumptions CLT makes can lead to some difference in results, but the majority of the difference comes from the definition of boundary conditions and loads. CLT cannot handle fixed edges and point loading. Nevertheless, CLT was found to be a useful tool for finding the best laminate, but not for finding accurate deflections. However, numerical simulation provided accurate results. It predicted a 6.7° twist, which is close to the experimental result.

The conclusion is that the proposed process for the optimization of coupled composite layup is usable. The analytical tool finds the best layup for a given non-conventional shape change, and the numerical simulation predicts the actual deflections with good accuracy. Furthermore, the magnitude of the twisting deformation in response to bending moment was great enough to promise significant aerodynamic advantages when used as a racecar diffusor. Fluid dynamics simulations can help evaluating these advantages in the future.

3 MITIGATION OF THERMAL WARPING

Composites with non-symmetric layups tend to warp in response to thermal loading. The reason for this is the unbalanced thermal expansion or shrinkage of the plies. This causes unwanted out-of-plane deformations right at the manufacturing step. The cross-linking reaction of the thermoset matrix of composites almost always occurs at an elevated temperature. At that temperature, the laminate is in energy minimum in terms of thermal stresses. As soon as the temperature changes, thermal stresses lead to in-plane deformations in the plies. If the composite layup is symmetric, these deformations do not lead to out-of-plane deformations of the laminate. However, if the layup is non-symmetric, the thermal stresses do not cancel each other out, and the laminate warps. This is a serious issue, which needs to be addressed, otherwise the advantages of non-symmetric composites cannot be exploited.

This section proposes two possible ways to mitigate thermal warping of composites with non-symmetric layups.

3.1 Compensation of warping with curved tools

This concept builds on controlled warping. It is best to exemplify the approach with a simple case: let us say that the goal is to manufacture a flat composite panel with non-symmetric layup. Then, we would use a curved tool to do so. The curvature of the tool needs to be designed so that during the cooling step of the manufacturing process, the laminate would warp to the desired flat shape. The concept should work even in case of components with more complex shapes. Of course, the tool is difficult to design in such a case. However, numerical optimization should be able to tackle these problems and provide the optimal tool shape for a given laminate and given temperatures (curing temperature and operational temperature).

3.2 Mitigation of warping with hybrid composites

Thermal warping can be mitigated with hybrid composites. This would mean using at least two different kinds of plies in the layup. The plies would naturally differ in mechanical properties (most importantly in moduli) and thermal expansion to some extent. However, it is most likely that they would not differ to the same extent in stiffness and thermal expansion. As a result, it is possible to design non-symmetric layups where out-of-plane thermal stresses (nearly) cancel each other out while the wanted coupling behaviour (originating from the stiffness values) does not vanish completely. The greatest advantage of this approach compared to the curved tool method is its temperature independence.

3.3 Limitations and potential

There is a trade-off for both warping mitigation concepts. As the hybrid layup approach builds on balanced out-of-plane thermal stresses, the number of possible layup permutations with the wanted coupling behavior becomes significantly decreased. The maximal achievable coupling deformation is likely to decrease, too.

The curved tool method is limited by its temperature dependence. As this method builds on controlled warping, a change in temperature would result in an underwarped or overwarped shape. On the other hand, this phenomenon has great potential in the right application. Temperature actuated morphing composites can be advantageous in numerous industrial fields, such as the aerospace industry, where temperatures during takeoff and landing are significantly different from those during flight.

4 SUMMARY

We introduced a layup optimization process for coupled composites by presenting a case study, where the layup was optimized for a morphing race car diffusor. The analytical and numerical results were compared to experimental data. The analytical optimization tool was found to be suitable for finding the best layup, but for accurate deflections, numerical modelling was needed. The more than 6° twisting of the 180 mm x 180 mm laminate at 30 mm mid-point deflection is considered to be great enough to lead to significant aerodynamic advantages. In sum, the coupling behavior is significant and its optimization process works.

Coupled composites often have non-symmetric layups, which leads to thermal warping. Two warping mitigation methods were proposed. The working principle of the first method is controlled warping to the desired shape from undercurved or overcurved tools. The disadvantage of this method is its temperature dependence. However, it opens up another possible use-case of composites: temperature actuated shape changing composites. The other proposed way to mitigate thermal warping while maintaining some of the coupling characteristics is designing hybrid composites. Both methods need further investigation but there is no reason why they could not work well.

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