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Combining Simulation-Based Design Techniques for Optimizing Fibre-Reinforced Polymer Parts

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Highlights

- A method for optimizing topology and parameters of composite structures.
- Large potential structural performance gains.
- No requirement for composite expertise and experience.
- Easy validation through FE analysis.

Abstract

Due to their inherent anisotropic properties, designing composite parts is challenging. It takes experience and deep insight to design a part that is both efficient in material usage and sufficiently stiff or strong.

This thesis shows that Simulation-based Design is possible with anisotropic composites, such as carbon fiber reinforced polymers. Combining both non-parametric and parametric optimization methods, a part is generated with minimal design inputs from the designer. The part is shown to vastly outperform its conventional made counterpart with the same weight.

A 76% decrease of maximum deflection and a 62% decrease of maximum in-plane Mises stress was simulated in the validation stage. A combination of an optimized shape, i.e topology, and an optimized composite ”recipe” leads to better utilization of each fiber.

Keywords: Topology optimization; Composite materials; Parametric optimization

Introduction

In today's quest for more efficient, lighter and stronger parts, composites has become an important pillar in the manufacturing realm. Most industries are in one way or another involved with composite parts, be it a carbon fibre monocoque car chassis, a fibreglass boat hull or a composite golf club.

Designing and manufacturing composite parts is challenging. Due to the anisotropic properties of composites, determining their internal stress situation is not trivial[4].It takes experience and deep insight to design a part that is both efficient in material usage and sufficiently stiff or strong.

The rise of Simulation Based Design, combined with the shape possibilities of additive manufacturing has led to some groundbreaking designs made from isotropic materials[1]. It is natural to think that the next logical step is to apply simulation driven design technologies to composites.

This article describes a novel approach, with minimal inputs, to let computer processing power generate both the optimal part topology as well as the "recipe" for the optimal composite composition. This will be achieved through a two step process where the first step generates the optimal part topology, and the second step generates an optimal layup configuration.

This will not only unlock the next level of structural performance for composite constructions, but also lessen the need for human expertise in the design phase, while also reducing material costs.

If the loading and boundary conditions, the material properties, the available design space and the problem constraints (i.e. factor of safety(FoS) or weight goal) are known, it could be possible to generate a part topology and layup recipe that would outperform the equivalent traditional composite part, no matter the composite experience of the designer.

Method and Procedure

The design optimization process developed consists of utilizing several, well known engineering methods. Descriptions of the methods used are presented in this chapter, and an overview of the design process and procedure is graphically illustrated in Figure 1.

Composite materials are made up by two or more materials with different properties that, when combined yields a material with different characteristics from the individual components. This paper will focus solely on a sub-division of composites called Fibre-reinforced polymers (FRP). FRP is a composite material that consist of a polymer matrix reinforced with fibres.

Using modern computer tools and algorithms, **Simulation-based Design (SBD)** enable the possibilities to design more efficient, sophisticated designs. Using a combination of 3D-modelling, simulation and optimization solvers, any design can be optimized according a given input. With SBD, the traditional iterative engineering design process are replaced with a more efficient computer-driven process, resulting in better, more optimum designs[7].

A combination of non-parametric and parametric optimization methods are used. The non-parametric method, topology optimization, is executed first to obtain an optimum geometry of a given component or structure. Subsequently, the parametric optimization method utilizing an evolution based algorithm, is executed to define the optimum material layup configuration of the FRP-material.

Topology optimization is a mathematical method used to optimize the material distribution for a defined design space, according to given model inputs and the objective function of the optimization solver. The objective function is defined as the "minimum compliance problem," where minimizing the compliance i.e. strain energy leads to maximizing the stiffness of the construction[5].

The output from the topology optimization is sliced into thin cross sections, at the height of one lamina ply. Projected to the ground plane, these will be the boundaries of each ply.

After the geometry is optimized from the topology optimization process, the evolution-based parametric optimization model to define the layup is executed. The relevant variables are mapped to the design variables in the process. The ply angles are optimized in this example. The goal is to minimize the total elastic strain energy, hence, maximizing the stiffness of the part.

A prescript constructs and applies a given layup configuration to the model before each iteration. By varying the parameters in the prescript, different layup configurations can be tested. After each iteration, the strain energy value is fed into the Evol algorithm and the design variables are adjusted. The process is illustrated in Figure 2.

To **validate** the resulting geometry and layup, a part with similar mass and a conventional layup[3] is compared to the optimized part. The "benchmark" part will have identical footprint, but uniform thickness and a alternating 0/ $\pm$ 45/90 degree layup.

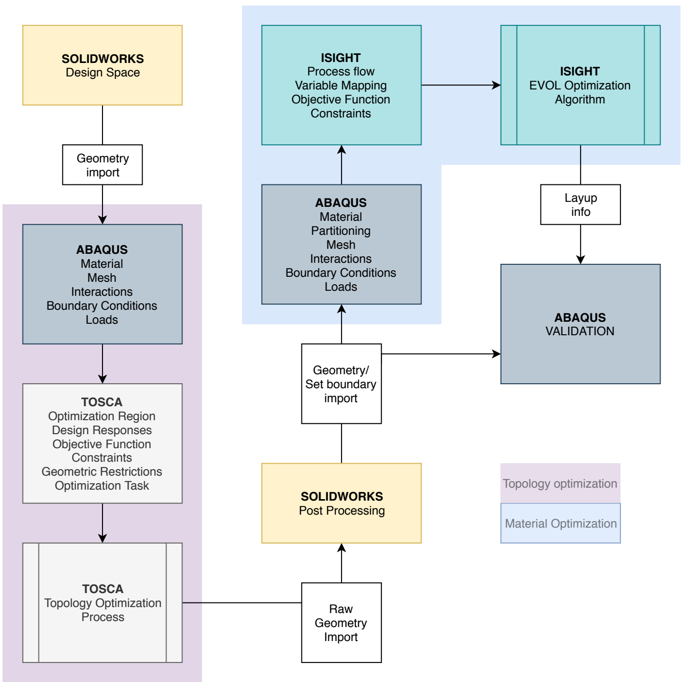

Figure 1: Total Design Process Flowchart

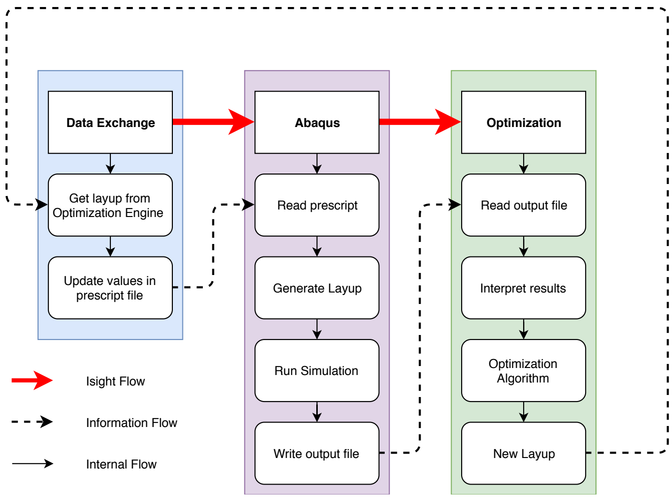

Figure 2: Process Flowchart

Results

The **Topology optimization** process converged and met the stopping conditions after 24 iterations. Figure 3 presents the design space, raw output and processed geometry. Figure 4 illustrates the 4 different sections that each contains 5 plies.

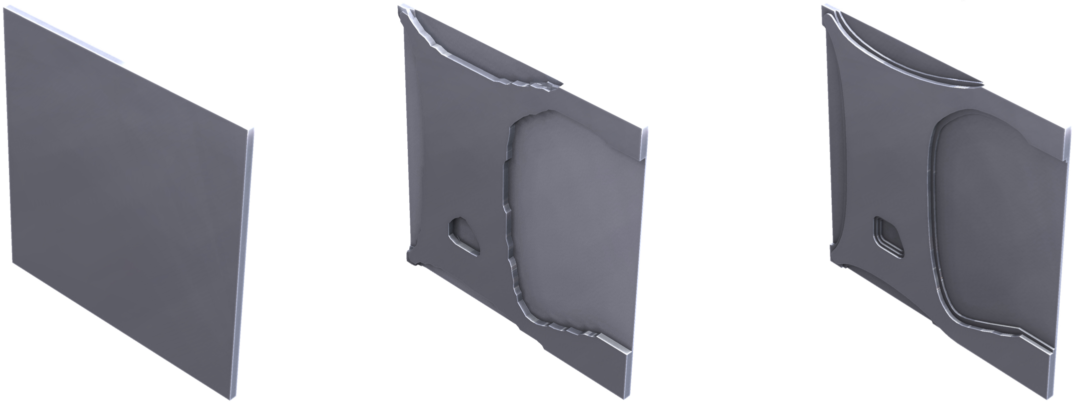

Figure 3: Design Space, Raw geometry, Processed geometry

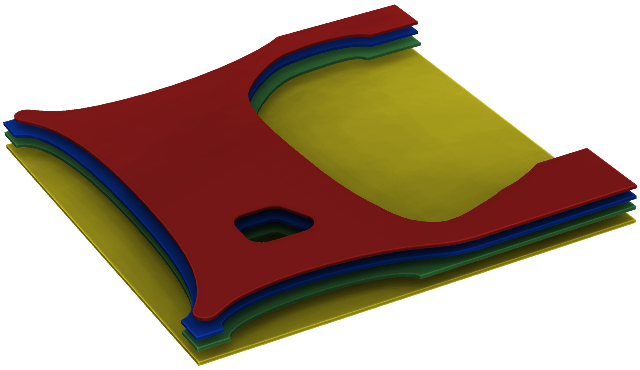

Figure 4: Exploded view of the ply sections

The **material optimization** process converged and met the stopping conditions after 850 iterations. Iteration 835 gave the best results. The composite stacking sequence with the corresponding ply angles is shown in Figure 5.

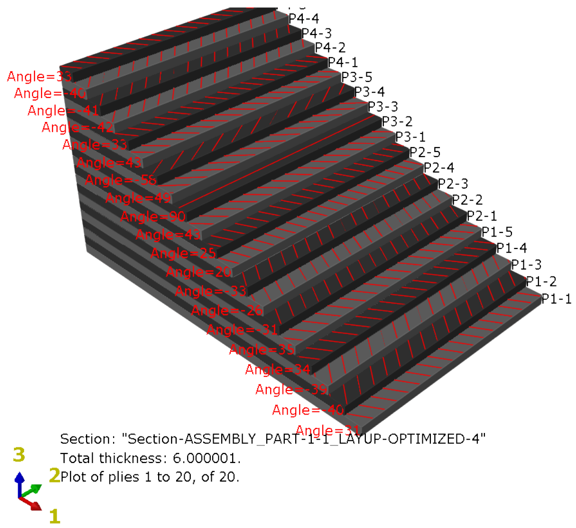

Figure 5: Visualized stacking sequence

The **validation** results is tabulated in table 1. The volume, and therefore weight is within 99% of each other.

Part	Thickness	Volume mm^2	Layup	Strain Energy J/mm^3	Maximum Deflection mm	Max In-plane Mieses stress MPa
Optimized part	6mm	$1.46E+05$	Optimized Layup	$134,795$	$2.6E-01$	$6.86E00$
Conventional part	3.6mm	$1.44E+05$	$0/\pm45/90$	554	$1.09E00$	$1.79E01$

Table 1: Validation Results

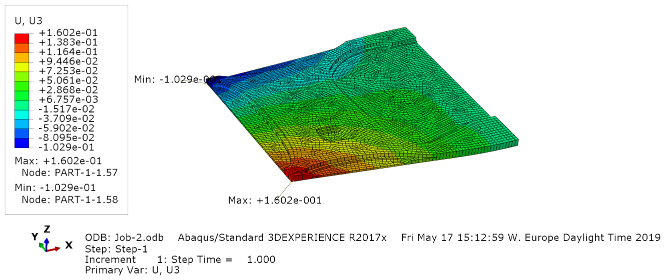

Figure 6: Maximum displacement of optimized part

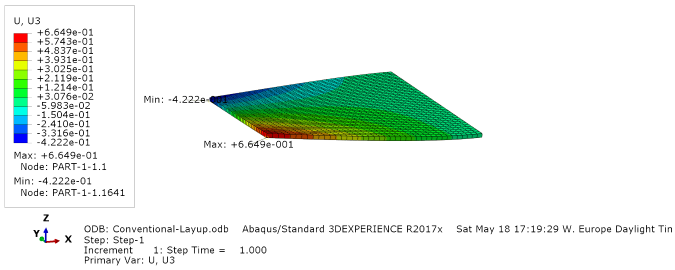

Figure 7: Maximum displacement of conventional part

Discussion

Where as this this process can let designers with little composite experience and insight, design sophisticated parts, it demands a greater insight into the constraining properties, such as the loading scenarios and boundary conditions. There is, most likely, less headroom for unforeseen loading conditions with this process, compared to a traditional layup. This also implies that the process is most eligible for part design when there is little uncertainty about the actual conditions the part will operate in. However, it is entirely possible to define loading conditions that are not expected to happen, and still desirable to have safety margins for.

With regards to manufacturability, taking special consideration in the design process is crucial to obtain high quality components. The output geometry of a topology optimization process often has "organic" shapes and complex geometry. This is not favourable for composite parts, since the plies frays easily if the ply shape or size become too intricate or small. Plies can also shift in relation to each other during moulding. This can somewhat remedied by using a finer mesh resolution transversely through the part.

The sections transversely through the part should, for an even more optimized layup, be further sectioned. The loading conditions in one plane could vary, and when all of the fibers in that plane have the same direction, it is safe to say that not all of the fiber strength can be utilized effectively. A novel solution to this problem might be a sub-step where each layer further optimized, similar to the approach of Lee, Kim, et al [2]. Work was started on a software that split the different cross sections into more composite friendly sub sections, by looking for ways to split each partition into few, but large and uniform pieces. Due to time restrictions, this was not finished. .

An option to include a hollow or a low density core would be of interest [6]. Beam constructions will have little in-plane stress and strain near the neutral plane, rendering the fibers in this area potentially not fully utilized.

The process is highly scalable. At the expense of solving time, one could easily implement variables for several different properties, such as, material type or different load scenarios. For manufacturing ease, one could limit the available ply angles and allowable values. In theory, every constraint, variable or value in the regular finite element analysis could be implemented in the iterative material optimization process.

Conclusion

A design process for optimizing composite structures, including part topology and layup configuration have been successfully developed and executed. The presented example indicates significant increase in part performance compared to traditional structures. However, the process still needs refining prior to designing actual real world parts. Nevertheless, the potential benefit of utilizing tailored processes to design complex composite parts are evident.

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