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Combining Simulation-Based Design Techniques for

Optimizing Fibre-Reinforced Polymer Parts

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Abstract

In today's quest for more efficient, lighter, stronger and more robust parts, composites has become an important pillar in the manufacturing realm. With increasing performance demands, the more complex the design and production phase becomes.

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. Chances are, with any great performing composite part today, a significant credit must be given to the designers past experience and composite knowledge.

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.

There is little doubt that a paradigm shift is in store for composites, where processing power soom will be designing parts that us humans never would have dreamt of.

Kombinering av simuleringsbaserte designteknikker for å optimalisere fiberforsterkede polymer-deler

Sammendrag

I dagens søken etter mer effektive, lettere, sterkere og mer robuste deler, har kompositter blitt en viktig del i produksjon generelt. Når kravene til ytelse øker, blir både design- og produksjonsprosessen mer kompleks.

På grunn av de anisotrope egenskapene til kompositter er designprosessen utfordrende. Man trenger dyp innsikt og lang erfaring for å designe konstruksjoner som både er effektive i materialbruk, samt oppfyller kravene for f.eks. styrke eller stivhet. Har man en godt designet komposittdel i dag, så har man mest sansynlig designerens lange erfaring og dype innsikt å takke.

Denne avhandlingen viser at simuleringsbasert design er mulig for anisotrope kompositter, som f.eks. karbonfiberforsterkede polymerer. Ved å bruke både ikke-parametriske og parametriske metoder for optimalisering, så vil man kunne generere en konstruksjon eller del, med minimale instruksjoner fra designeren. Den optimaliserte delen i denne avhandlingen yter langt bedre enn den tilsvarende, konvensjonelle delen med lik vekt.

Maksimal avbøying ble senket med 76%, og maksimal Mises plan-spenning ble senket med 62% i valideringen. En kombinasjon av optimal geometri, samt optimal oppbygning av komposittkonstruksjonen gjør at hvert fiber er bedre utnyttet.

Det er liten tvil om at det venter et paradigmeskifte i komposittverden, der datakraft designer deler som vi mennesker aldri hadde drømt om.

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1
Introduction

In today's quest for more efficient, lighter, stronger and more robust 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. Once done right, composite parts can vastly outperform their traditional made counterparts.

Designing and manufacturing 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.

Due to the highly anisotropic properties of composites, determining their internal stress situation is not trivial[4]. The lack of awareness of the actual stress situation is usually counteracted with excessive material usage, rendering the part both heavier and more expensive than necessary. Even overbuilt composite constructions outperform its steel or aluminium counterpart when it comes to strength or stiffness versus weight.

For many years, the usage of Finite Element analysis (FEA) has given designers and engineers the ability of easily validating their design, both with composites and especially with traditional materials.

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, since this is not easily available yet.

This thesis will describe a novel approach, with minimal inputs, to let computer calculating 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.

A thin beam segment reminiscing a structure typical for an alpine ski construction is optimized using the developed design process in this thesis. The structure is constrained on one vertical side, exerted to a torsional load on the opposing side, in addition to a distributed load underneath the structure. All practical results presented is from optimizing this geometry.

1.1 Motivation

This is a culmination of a life-long interest in composites, usually in the form of carbon fiber bicycle frames and rims, or alpine skis. An seemingly innate ability to never be satisfied with the performance of various equipment and sporting goods, has led to the pursuing of a mechanical engineering degree, as well as several spare-time projects involving both composites and mechanical parts.

2
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 2.1.
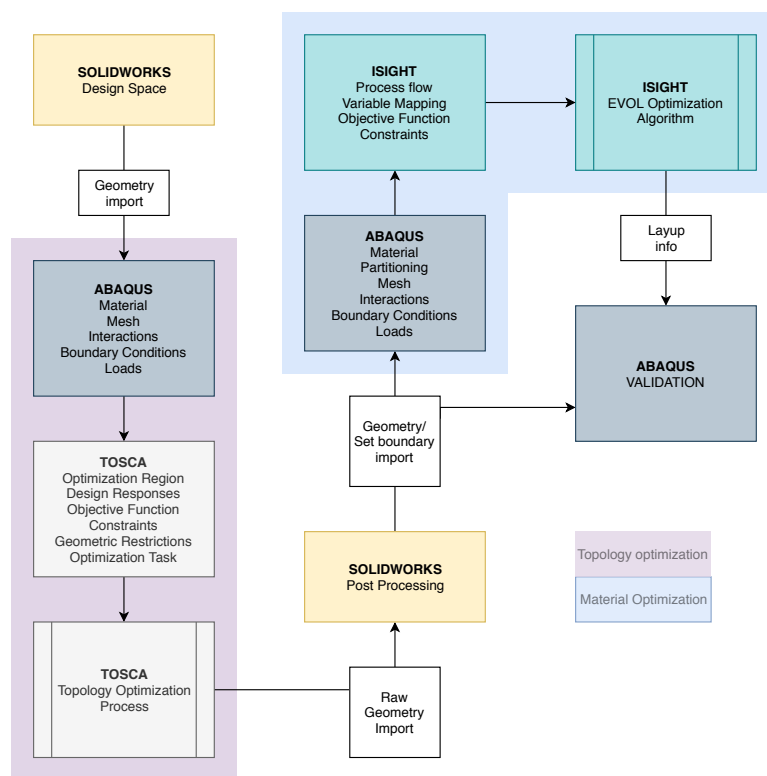

Figure 2.1: Total Design Process Flowchart

2.1 Composites

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. Even though composites describes a

broad spectrum of materials, such as reinforced concrete, 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. The matrix is usually an epoxy and the fibers is usually glass fibre or carbon fibre.

2.2   Layup

The composite parts that will be relevant for this thesis consists of stacked layers of fiber with a set fiber-to-resin content. One of these layers is called a ply. The fiber comes pre-impregnated with resin with an optimal ratio, usually around 40 percent resin content.

2.3   Simulation-based Design (SBD)

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].

In this thesis, a combination of non-parametric and parametric optimization methods are used. The non-parametric method, utilizing topology optimization is executed first to obtain an optimum geometrical layout of a given component or structure. Subsequently, a parametric optimization method utilizing an evolution based algorithm is executed to define the optimum material layup configuration of the FRP-material. An overview of the optimization model used is presented in Appendix A.

2.4   Computer-aided Design (CAD)

The initial part of the SBD-method, is to define a 3-dimensional design space remedying the available physical space for the component. The design space is defined in the Computer-aided Design (CAD) software, SOLIDWORKS. The design space is defined to include all relevant geometrical features required for the final component, and features considered to influence the optimization results.

2.5   Finite Element Analysis (FEA)

Once the design space is defined, the model is transferred to the finite element analysis (FEA) software Abaqus, in the neutral cad file format parasolid/Step/etc. FEA is a numerical mathematical method used to solve physics and engineering problems. FEA can be used to solve a range of different problems, however, in this thesis the structural analysis part of FEA is used.

In Abaqus, the model is discretized into finite elements, and the material for the topology optimization process is selected. The boundary conditions and loading scenarios are defined, including any necessary geometrical interactions. Later on, the FRP-material and layup definitions are also modelled in Abaqus.

2.6 Topology Optimization (TO)

Once the FE-model is defined, the topology optimization model is developed in the Tosca Structure optimization software. Tosca Structure is run from within the Abaqus graphical user interface. 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 topology optimization set up can be shown in table2.1. An arbitrary isotropic and elastic material with a elastic modulus E=50 GPa was applied. It was expected that the strain would be fully elastic. As long as the loading condition are identical to that of the material optimization process, the elastic modulus should be set at a value that gives small initial displacements, so that eventual nonlinear strain does not occur. The elastic modulus for the isotropic design space should in any case be significantly less than the equivalent anisotropic lamnia values. The unidirectional fibres used in this thesis have an elastic modulus of 164 GPa along the fibers. A similar woven fabric has a elastic modulus of E=65 GPa in 2 principal directions.

The output from the topology optimization process undergoes some conditioning before it is sliced into thin cross sections, at the height of one lamina ply. If the part is 6mm thick, and each ply is 0.3mm, you would have 20 cross sections. Each cross section has a corresponding ply, and when the ply is stacked on top of each other, the resulting composite part will closely match the geometry of the topology optimization output.

Material	Elastic
Element type	Strctured Hexahedral
Design response	Strain energy, volume
Objective function	Minimize strain energy
Constraints	Volume target
Geometric constraints	Forging constraint, frozen load sections
Max.cycles	50

Table 2.1: Topology Optimization Set-up

2.7   Material Optimization

After the geometry is optimized from the topology optimization process, the evolution-based parametric opti-
mization model to define the FRP-material layup is executed. This process is run through the process automa-
tion and design exploration software Isight. The relevant variables are mapped to the design variables in the
process. In this case, the only parameters which are optimized, are the ply angles in the FRP layup. The goal
is to minimize the total elastic strain energy, hence, maximizing the stiffness of the part.

A Python prescript constructs and applies a given layup configuration to the model in Abaqus before each
iteration. By varying the parameters in the prescript, different layup configurations can be tested. After each
iteration, Isight reads the output .odb file and extracts the strain energy value. This value is fed into the Evol
algorithm and the design variables are adjusted. A process application called "Data Exchanger" is used to
manipulate the prescript before each iteration. The process is illustrated in Figure 2.2 and Figure 2.3.
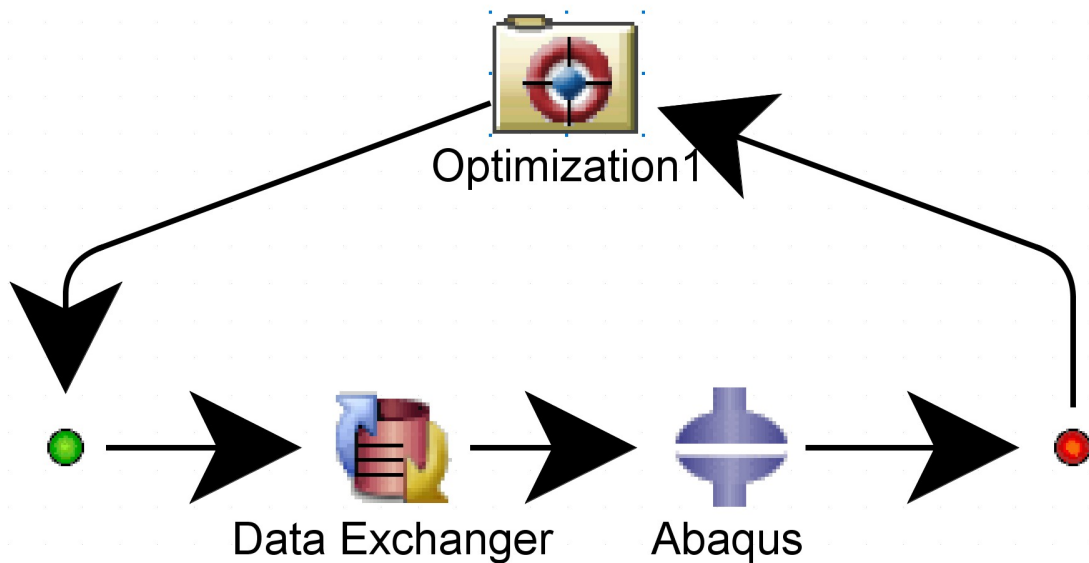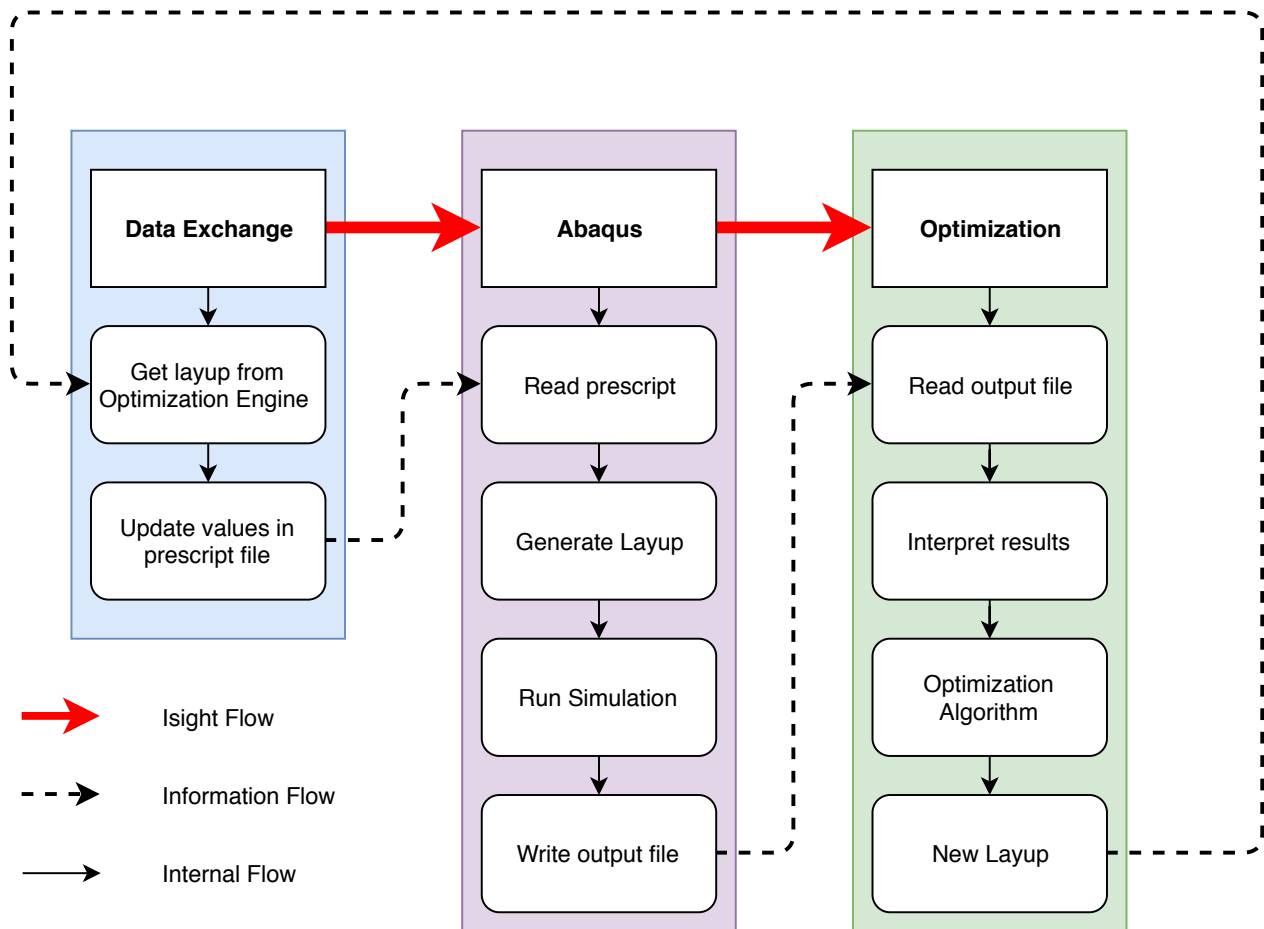

Figure 2.2: Isight GUI Flowchart

Figure 2.3: Process Flowchart

2.8   Lamina Properties

The material in this setup is a unidirectional pre-impregnated carbon fibre. A suitable material was found and the engineering constants can be found in table 2.2. The data sheet can be found in the appendixC.

E1	E2	Nu12	G12	G13	G23
164 GPa	9 GPa	0.31	6.5 GPa	6.5 GPa	6.5 GPa

Table 2.2: Hexcel 6376 UD

2.9   Validation of Conventional layup

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.

3
Results

3.1 Topology Optimization Results

From the the optimization suite in Abaqus and Tosca, a raw, faceted geometry is exported for post processing in Solidworks. The optimization process converged and met the stopping conditions after 24 iterations, shown in Figure 3.1. Figure 3.2 and Table 3.1 presents the design space, raw output file and the processed geometry and corresponding volume content, respectively. Figure 3.3 illustrates the 4 different sections that each contains 5 plies.
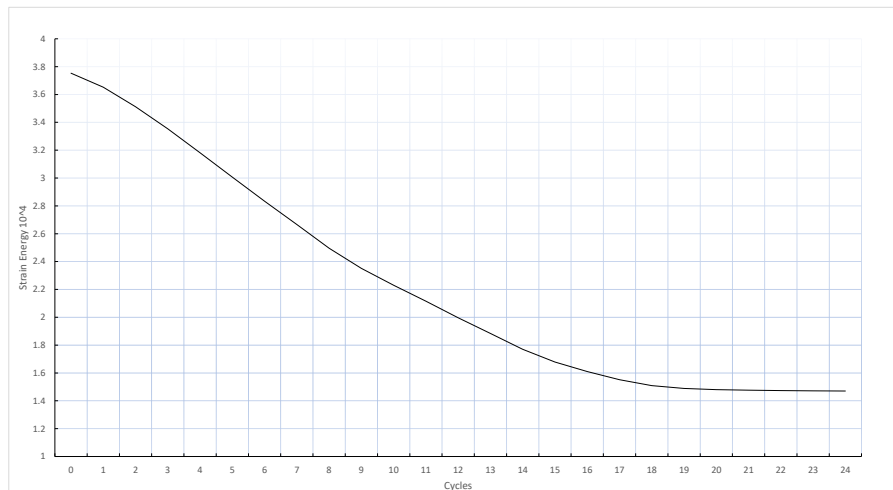
Figure 3.1: Convergence graph for topology optimization process

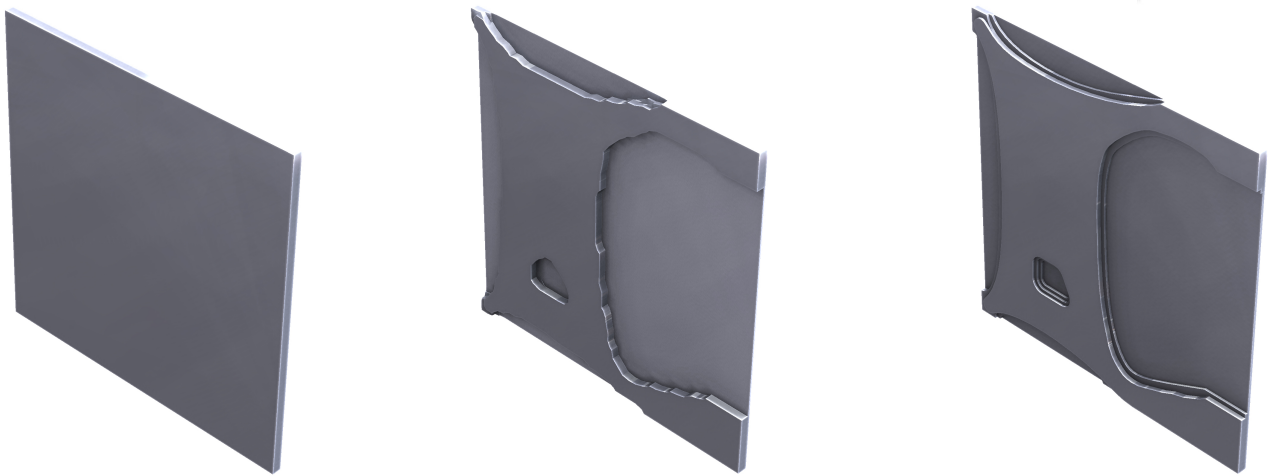|	Design Space	Raw File	Processed File
Volume $[mm^3]$	2.40E+05	1.26E+05	1.46E+05
% of design space	100 %	52.5 %	60.83 %

Table 3.1: Volume content of part topology

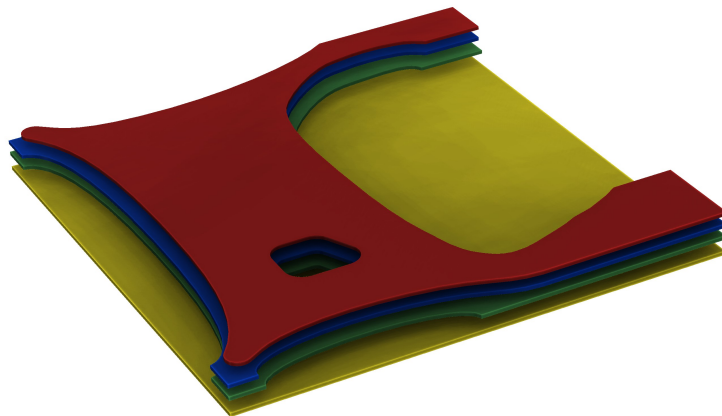Figure 3.2: Design Space, Raw geometry, Processed geometry

Figure 3.3: Exploded view of the ply sections

3.2 Material Optimization

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 are shown in Table 3.2 and Figure 3.4. The iterations are plotted in Figure 3.5.
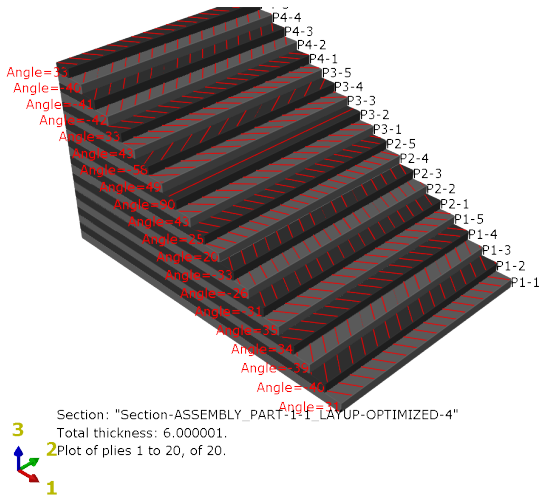

Figure 3.4: Visualized stacking sequence

Ply	Region	Fiber Direction
1	SET-1	31
2	SET-1	-40
3	SET-1	-39
4	SET-1	34
5	SET-1	35
6	SET-2	-31
7	SET-2	-26
8	SET-2	-33
9	SET-2	20
10	SET-2	25
11	SET-3	43
12	SET-3	90
13	SET-3	49
14	SET-3	-58
15	SET-3	43
16	SET-4	33
17	SET-4	-42
18	SET-4	-41
19	SET-4	-40
20	SET-4	33

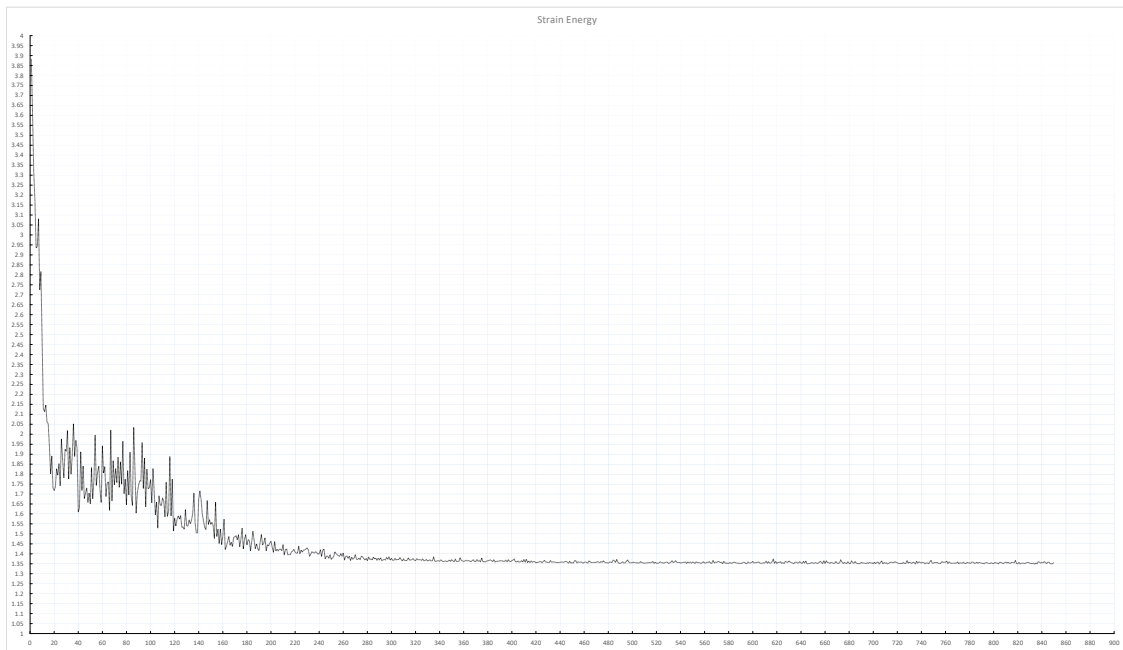Table 3.2: Optimized ply orientation

Figure 3.5: Strain Energy development

3.3   Validation

The validation results is tabulated in table 3.3. The volume, and therefore weight is within 99% of each other.

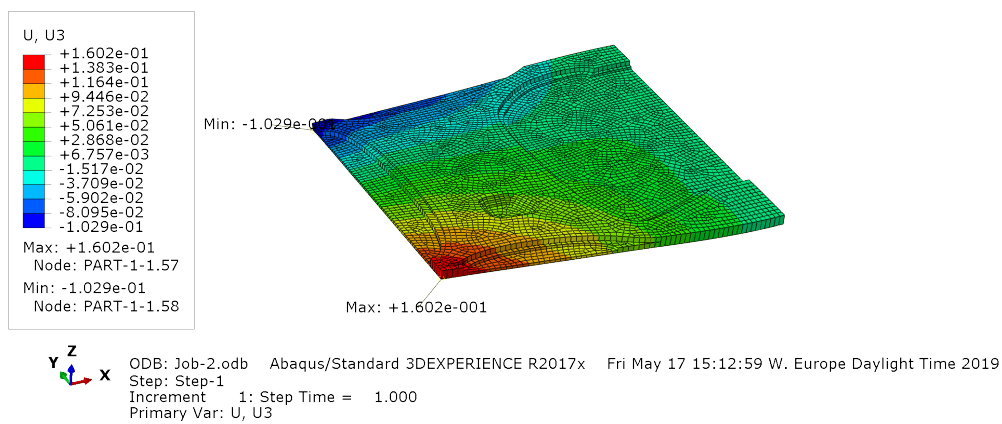| Part	Thickness	Volume mm^2	Layup	Strain Energy J/mm^3	Maximum Deflection mm	Max In-plane Mieses stress MPa
Optimized part	6mm	$1.46E+05$	Optimized Layup	$134,795$	$2.6E-01$	$6.86E00$
Conventional part	3.6mm	$1.44E+05$	$0/\pm45/90$	554	$1.09E00$	$1.79E01$

Table 3.3: Validation Results

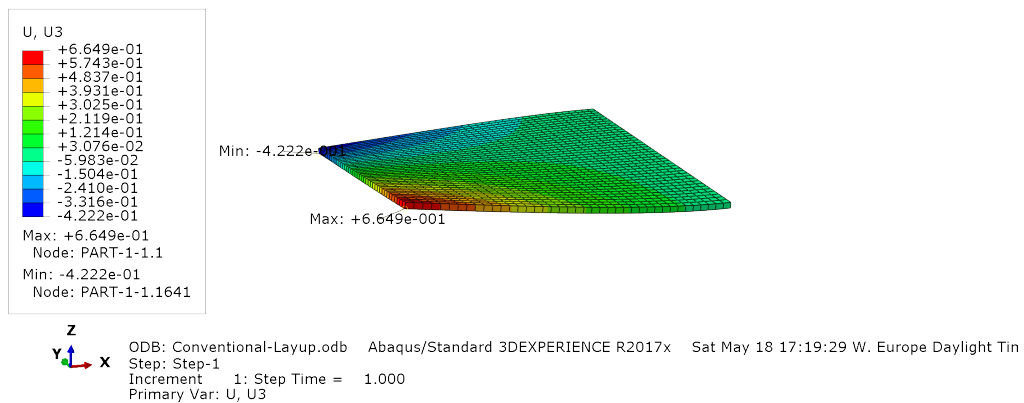Figure 3.6: Maximum displacement of optimized part

Figure 3.7: Maximum displacement of conventional part

4
Discussion

Due to time restrictions, it was not possible to test the procedure on different geometries, boundary conditions and loading scenarios. The goal with the process and the reasoning behind the actual loading scenario and geometric restrictions chosen in this thesis, was to come closer to a viable method for designing long, flat constructions, such as an alpine skis, a snowboard or a skateboard deck. The method need refining before the the process is applicable for designing real world parts.

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 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.

Even though the topology optimization process has a volume constraint, the resulting raw solid geometry can have some deviations. The optimized geometry in the software consists of a set of elements with a given individual volume weight. For exporting the optimized results from Abaqus, translating the results to a faceted surface, some slight discrepancy must be expected. Some simplification of the output geometry from the topology optimization process was necessary to ensure that the meshing process for the material optimization step was successful. The edges of the topology optimized geometry was close to vertical, and that lead to very small distances between the contour lines of the different sets. The problem is illustrated in Figure 4.1. These lines is projected onto the base plane for sectioning in Abaqus. The mesh needs to conform with these contour lines, because these lines make up the outside edges of the different height steps on the finished part. If the cross section had varied more, the issue would be less prominent.
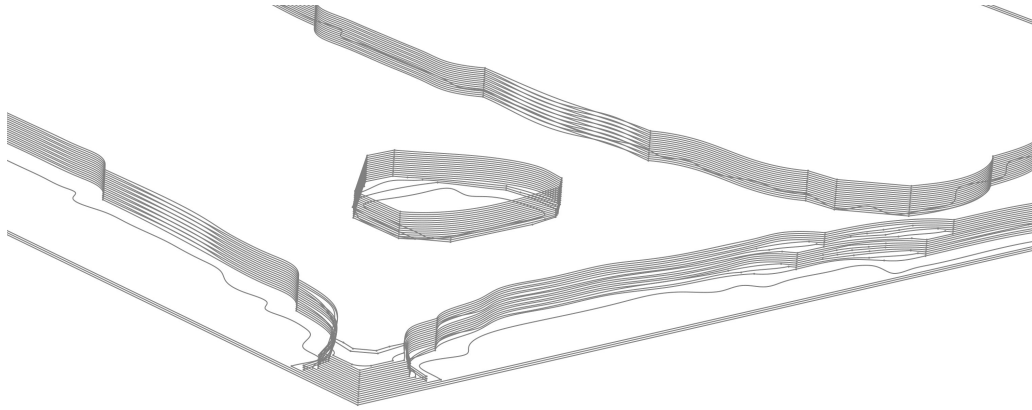
Figure 4.1: Overlapping contour lines

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. Some assurance towards composite manufacturability has been done, such as meshing the design space geometry with a fine mesh transversely, and a bit coarser in the in-plane directions. In this case, though, the cross section geometries were sufficiently coarse, so that any composite manufacturer would be able to cut the fabric in the shapes necessary.

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]. It is widely known that even slender beam constructions will have little in-plane stress and strain near the neutral plane, rendering the fibers in this area potentially not fully utilized. In addition, a low density core would result in a larger longitudinal cross section for the same part weight, which would be beneficial for bending stiffness.

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.

5
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.

A
Model Definition

Design space is a cuboid with the dimensions $WxLxH = 200x200x$mm.

The part is fully encastered on one side. The opposing corners, each have a point force applied, with opposite directions. Each of these forces are 10N. In addition, there is a distributed force acting on the underside of the part, with a total force of 5N. These loading conditions gives torsional and bending loading on the part, respectively.
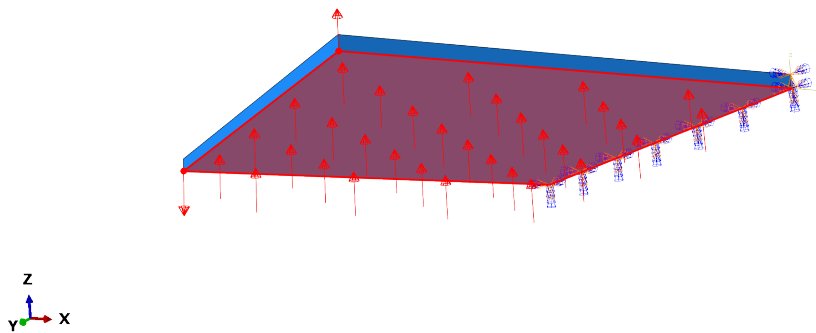

Figure A.1: Loads and Boundary Condition

B
Python Code

The python pre-script

```python
# −∗− coding : mbcs −∗−
# Do not delete the following import lines
from abaqus import *
from abaqusConstants import *
import __main__


import section
import regionToolset
import displayGroupMdbToolset as dgm
import part
import material
import assembly
import step
import interaction
import load
import mesh
import optimization
import job
import sketch
import visualization
import xyPlot
import displayGroupOdbToolset as dgo
import connectorBehavior
layupOrientation = None
p = mdb. models [ 'Model−1' ]. parts [ 'Part−1' ]

region1=p. sets [ 'P1' ]
region2=p. sets [ 'P2' ]
region3=p. sets [ 'P3' ]
region4=p. sets [ 'P4' ]

compositeLayup = mdb. models [ 'Model−1' ]. parts [ 'Part−1' ]. CompositeLayup (
    name='Layup2', description='', elementType=SHELL,
    offsetType=BOTTOM_SURFACE, symmetric=False,
```

```python
36      thicknessAssignment=FROM_SECTION)
37  compositeLayup.Section(preIntegrate=OFF, integrationRule=SIMPSON,
38      thicknessType=UNIFORM, poissonDefinition=DEFAULT, temperature=GRADIENT,
39      useDensity=OFF)
40  compositeLayup.ReferenceOrientation(orientationType=GLOBAL, localCsys=None,
41      fieldName='', additionalRotationType=ROTATION_NONE, angle=0.0,
42      axis=AXIS_3)
43
44  compositeLayup.CompositePly(suppressed=False, plyName='P1-1',
45      region=region1, material='UD', thicknessType=SPECIFY_THICKNESS,
46      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=11.0,
47      additionalRotationType=ROTATION_NONE, additionalRotationField='',
48      axis=AXIS_3, angle=0.0, numIntPoints=3)
49
50  compositeLayup.CompositePly(suppressed=False, plyName='P1-2',
51      region=region1, material='UD', thicknessType=SPECIFY_THICKNESS,
52      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=12.0,
53      additionalRotationType=ROTATION_NONE, additionalRotationField='',
54      axis=AXIS_3, angle=0.0, numIntPoints=3)
55
56  compositeLayup.CompositePly(suppressed=False, plyName='P1-3',
57      region=region1, material='UD', thicknessType=SPECIFY_THICKNESS,
58      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=13.0,
59      additionalRotationType=ROTATION_NONE, additionalRotationField='',
60      axis=AXIS_3, angle=0.0, numIntPoints=3)
61
62  compositeLayup.CompositePly(suppressed=False, plyName='P1-4',
63      region=region1, material='UD', thicknessType=SPECIFY_THICKNESS,
64      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=14.0,
65      additionalRotationType=ROTATION_NONE, additionalRotationField='',
66      axis=AXIS_3, angle=0.0, numIntPoints=3)
67
68  compositeLayup.CompositePly(suppressed=False, plyName='P1-5',
69      region=region1, material='UD', thicknessType=SPECIFY_THICKNESS,
70      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=15.0,
71      additionalRotationType=ROTATION_NONE, additionalRotationField='',
72      axis=AXIS_3, angle=0.0, numIntPoints=3)
73
74  compositeLayup.CompositePly(suppressed=False, plyName='P2-1',
75      region=region2, material='UD', thicknessType=SPECIFY_THICKNESS,
76      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=21.0,
77      additionalRotationType=ROTATION_NONE, additionalRotationField='',
78      axis=AXIS_3, angle=0.0, numIntPoints=3)
79
80  compositeLayup.CompositePly(suppressed=False, plyName='P2-2',
81      region=region2, material='UD', thicknessType=SPECIFY_THICKNESS,
82      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=22.0,
83      additionalRotationType=ROTATION_NONE, additionalRotationField='',
84      axis=AXIS_3, angle=0.0, numIntPoints=3)
85
86  compositeLayup.CompositePly(suppressed=False, plyName='P2-3',
```

```python
87      region=region2, material='UD', thicknessType=SPECIFY_THICKNESS,
88      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=23.0,
89      additionalRotationType=ROTATION_NONE, additionalRotationField='',
90      axis=AXIS_3, angle=0.0, numIntPoints=3)
91
92  compositeLayup.CompositePly(suppressed=False, plyName='P2-4',
93      region=region2, material='UD', thicknessType=SPECIFY_THICKNESS,
94      thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=24.0,
95      additionalRotationType=ROTATION_NONE, additionalRotationField='',
96      axis=AXIS_3, angle=0.0, numIntPoints=3)
97
98  compositeLayup.CompositePly(suppressed=False, plyName='P2-5',
99      region=region2, material='UD', thicknessType=SPECIFY_THICKNESS,
100     thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=25.0,
101     additionalRotationType=ROTATION_NONE, additionalRotationField='',
102     axis=AXIS_3, angle=0.0, numIntPoints=3)
103
104
105 compositeLayup.CompositePly(suppressed=False, plyName='P3-1',
106     region=region3, material='UD', thicknessType=SPECIFY_THICKNESS,
107     thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=31.0,
108     additionalRotationType=ROTATION_NONE, additionalRotationField='',
109     axis=AXIS_3, angle=0.0, numIntPoints=3)
110
111 compositeLayup.CompositePly(suppressed=False, plyName='P3-2',
112     region=region3, material='UD', thicknessType=SPECIFY_THICKNESS,
113     thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=32.0,
114     additionalRotationType=ROTATION_NONE, additionalRotationField='',
115     axis=AXIS_3, angle=0.0, numIntPoints=3)
116
117 compositeLayup.CompositePly(suppressed=False, plyName='P3-3',
118     region=region3, material='UD', thicknessType=SPECIFY_THICKNESS,
119     thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=33.0,
120     additionalRotationType=ROTATION_NONE, additionalRotationField='',
121     axis=AXIS_3, angle=0.0, numIntPoints=3)
122
123 compositeLayup.CompositePly(suppressed=False, plyName='P3-4',
124     region=region3, material='UD', thicknessType=SPECIFY_THICKNESS,
125     thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=34.0,
126     additionalRotationType=ROTATION_NONE, additionalRotationField='',
127     axis=AXIS_3, angle=0.0, numIntPoints=3)
128
129 compositeLayup.CompositePly(suppressed=False, plyName='P3-5',
130     region=region3, material='UD', thicknessType=SPECIFY_THICKNESS,
131     thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=35.0,
132     additionalRotationType=ROTATION_NONE, additionalRotationField='',
133     axis=AXIS_3, angle=0.0, numIntPoints=3)
134
135 compositeLayup.CompositePly(suppressed=False, plyName='P4-1',
136     region=region4, material='UD', thicknessType=SPECIFY_THICKNESS,
137     thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=41.0,
```

```
138    additionalRotationType=ROTATION_NONE, additionalRotationField='',
139    axis=AXIS_3, angle=0.0, numIntPoints=3)
140
141 compositeLayup.CompositePly(suppressed=False, plyName='P4-2',
142    region=region4, material='UD', thicknessType=SPECIFY_THICKNESS,
143    thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=42.0,
144    additionalRotationType=ROTATION_NONE, additionalRotationField='',
145    axis=AXIS_3, angle=0.0, numIntPoints=3)
146
147 compositeLayup.CompositePly(suppressed=False, plyName='P4-3',
148    region=region4, material='UD', thicknessType=SPECIFY_THICKNESS,
149    thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=43.0,
150    additionalRotationType=ROTATION_NONE, additionalRotationField='',
151    axis=AXIS_3, angle=0.0, numIntPoints=3)
152
153 compositeLayup.CompositePly(suppressed=False, plyName='P4-4',
154    region=region4, material='UD', thicknessType=SPECIFY_THICKNESS,
155    thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=44.0,
156    additionalRotationType=ROTATION_NONE, additionalRotationField='',
157    axis=AXIS_3, angle=0.0, numIntPoints=3)
158
159 compositeLayup.CompositePly(suppressed=False, plyName='P4-5',
160    region=region4, material='UD', thicknessType=SPECIFY_THICKNESS,
161    thickness=0.3, orientationType=SPECIFY_ORIENT, orientationValue=45.0,
162    additionalRotationType=ROTATION_NONE, additionalRotationField='',
163    axis=AXIS_3, angle=0.0, numIntPoints=3)
164
165
166
167
168 p = mdb.models['Model-1'].parts['Part-1']
169 session.viewports['Viewport: 1'].setValues(displayedObject=p)
```

C
Datasheets

HexPly® 6376
175°C curing epoxy matrix

HEXCEL

Product Data Sheet

Description
HexPly® 6376 is a high performance tough matrix formulated for the fabrication of primary aircraft structures. It offers high impact resistance and damage tolerance for a wide range of high temperature applications.

Benefits and Features
- Excellent toughness and damage tolerance
- Simple straight-up cure cycle
- Controlled matrix flow for ease of processing
- Effective translation of fibre properties
- Good hot/wet properties up to 150°C

Resin Matrix Properties

Rheology

Gel Time
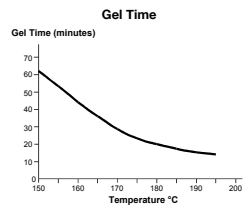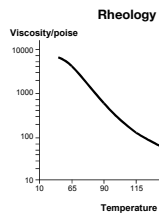
Cured Matrix Properties (cured at 175°C)

		Method
Tensile strength	105 MPa	ISO R527 type 1
Tensile modulus	3.60 GPa	ISO R527 type 1
Tensile strain	3.1%	ISO R527 type 1
Flexural strength	144 MPa	ISO 178
Flexural modulus	4.4 GPa	ISO 178
Toughness G_{1C}	432 J/m²	Tested in accordance with EGF Task Group on Polymers and Composites protocol.
Cured density	1.31 g/cm³	

1

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