# LIFECYCLE METRIC INTEGRATION IN LAMINATION PARAMETERS DESIGN SPACE FOR STRUCTURAL OPTIMIZATION OF VARIABLE STIFFNESS COMPOSITE STRUCTURES

Julien M.J.F. van Campen[1]

[1] Aerospace Structures and Materials, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, the Netherlands, j.m.j.f.vancampen@tudelft.nl, https://www.tudelft.nl/en/ae/organisation/departments/aerospace-structures-and-materials

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## ABSTRACT

Weight minimisation is currently the driving factor that determines the lifecycle impact of an aircraft structure. The amount of aircraft that are manufactured yearly is increasing. At the same time, the aviation industry is working on a transition to other energy sources to meet climate goals. This means that the dogma that aircraft structures by definition must have the best possible specific properties, regardless of the specific energy requirement for manufacturing and/or recycling may change. If this happens, the necessity to include lifecycle metrics already in the structural design of composite aircraft parts will increase. In the presented work a method is proposed to include the effect of the specific energy requirement during production already in the design process of a composite plate. The proposed method is applied to a uniaxially compressed plate. Two different composite materials are considered and the results for these materials are compared to a baseline aluminium plate. The energy required to manufacture a plate for both considered composite materials was found to be significantly higher than that of the baseline aluminium plate. The results show that reduced mechanical performance of a composite material can be compensated by adopting variable stiffness laminate design, enabling a weight reduction of up to 35% compared to the aluminium baseline plate. Further study will be required to see whether these results can also be obtained for existing materials and manufacturing processes. Notwithstanding, these first results indicate that the choice of composite materials over aluminium for aircraft structures is to be considered carefully, should the life cycle impact benefit of light-weighting aircraft structures become less dominant in the future.

## 1 INTRODUCTION

Human activity is likely to exceed planetary boundaries if no mitigating actions are taken. Aviation is one of the industries that particularly comes to mind when it comes to impact on the environment. The aviation industry mainly attempts to reduce its environmental impact by reducing the emission of $CO_2$ and ultra-fine particles (UFP) to the atmosphere during the operational life of an aircraft. The production of these emissions is caused by the combustion of fuel and is therefore directly linked to the weight of an aircraft. Considering a service life of 20 to 30 years for an A320-like aircraft any reduction in structural weight will accumulate into a significant reduction of $CO_2$-emissions. As a result, weight reduction is one of the main design drivers for aircraft structures. Fibre reinforced composites are therefore often chosen for aircraft structures, because of their specific properties (strength and/or stiffness over weight). In the current design practice, the amount of energy required to produce, for example, a CFRP (carbon fibre reinforced polymer) part using an autoclave cycle, and the fact that at best the part can be down-cycled at end of life, is considered to be outweighed by the cumulative reduction of $CO_2$-emissions.

There are two main reasons to reconsider the current design practice for aircraft parts: 1) the projected amount of passenger aircraft that will be built, and 2) the transition of the aviation industry to alternative energy sources like green hydrogen. In the year 2022 Airbus delivered 661 new commercial aircraft. [1] In the same year Boeing reported the delivery of 542 new commercial aircraft. [2] With a predicted growth of air transport of 4.3% per annum over the next 20 years [3] there will be a significant increase in the demand for engineering materials that are energy intensive to manufacture and process. The need to recycle decommissioned aircraft will grow with at the same rate, albeit offset by 20 to 30 years. In other words, there is an urgent need to integrate life cycle assessment (LCA) in the design process of aircraft structures. At the same time, the aviation industry is striving towards climate neutrality by the year 2050 [4]. As a result, the climate impact of a kilogram of structural weight in terms of $CO_2$-emmissions can be expected to reduce. Therefore, it seems logical that next to the climate impact of aviation a beginning is made with reducing the life cycle impact of aircraft as well.

This work is a first exploration by the author on how relevant life cycle metrics can be integrated in the structural design and optimization laminated composite structures. The objective of the work presented in this paper is to study how relevant life cycle metrics can already be included during the mechanical design and optimisation of a fibre-reinforced composite laminate; and to use this to obtain targets on mechanical performance for the development of recyclable composite material systems. This is achieved in the following way. In section 2, it will be discussed how the specific properties of a recycled composite laminate, which will be lower than for virgin material [5], can indirectly be included as constraints in the lamination parameter (LP) design space [6]. The three-step procedure [7] to design variable stiffness (VS) composite laminates that has been developed at Delft University of Technology will be introduced in section 3, as well as a method to design VS laminates that do not require fibre steering. The presented method will be applied to a simply supported uniaxially compressed plate, in section 4. An aluminium plate will be used as baseline design in terms of weight, buckling load, and energy requirement to recycle into a new plate. The same values will be obtained for a plate made from a fictional recycled fibre reinforced composite material. VS laminate design will be used to make up for the loss in material properties. Comparing the results of the optimised recycled composite plate with the aluminium baseline, is expected to give an indication for any potential performance improvements needed for the recycled material before it can outperform the aluminium structure in terms of life cycle impact. This paper will be wrapped up in a discussion section outlining further development of the presented method.

## 2 LIFE CYCLE METRICS IN LAMINATION PARAMETER SPACE

### 2.1 Lamination parameters

Lamination parameters (LP) [6] are twelve dimensionless parameters that can be used to describe the mechanical behaviour of a laminated composite fully for a given material system,

$$\begin{aligned}
\left(V_1^{\mathbf{A}}, V_2^{\mathbf{A}}, V_3^{\mathbf{A}}, V_4^{\mathbf{A}}\right) &= \int_{-\frac{1}{2}}^{\frac{1}{2}} \left(\cos 2\theta, \sin 2\theta, \cos 4\theta, \sin 4\theta\right) d\overline{z} \\
\left(V_1^{\mathbf{B}}, V_2^{\mathbf{B}}, V_3^{\mathbf{B}}, V_4^{\mathbf{B}}\right) &= 4\int_{-\frac{1}{2}}^{\frac{1}{2}} \overline{z}\left(\cos 2\theta, \sin 2\theta, \cos 4\theta, \sin 4\theta\right) d\overline{z} \\
\left(V_1^{\mathbf{D}}, V_2^{\mathbf{D}}, V_3^{\mathbf{D}}, V_4^{\mathbf{D}}\right) &= 12\int_{-\frac{1}{2}}^{\frac{1}{2}} \overline{z}^2\left(\cos 2\theta, \sin 2\theta, \cos 4\theta, \sin 4\theta\right) d\overline{z}
\end{aligned} \tag{1}$$

Eight out of twelve lamination parameters become (approximately) zero when a balanced and symmetric lay-up is considered. The remaining lamination parameter space can be visually represented as shown (Fig. 1).

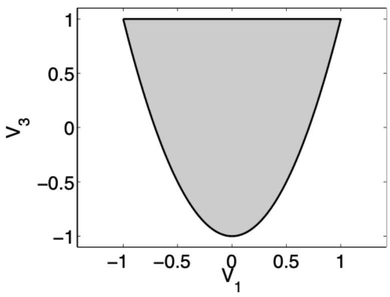


Figure 1. Feasible envelope in LP-space for in-plane and flexural LPs.

### 2.2 Material properties as function of specific energy required

For the purpose of this study the assumption is made that there exists a relationship between obtained strength and stiffness of the composite laminate, and the specific energy required (MJ/kg) for a given combination of recycling and manufacturing process [8], or in case of virgin composites, production process. It is expected that a more energy intensive process, e.g. applying more pressure or temperature in an autoclave, in general will lead to higher strength and/or stiffness of the part in question.

### 2.3 Strength constraints in lamination parameter space

There is no direct way to include life cycle metrics into the LP design space, therefore an indirect approach is followed. In literature, varying reductions in strength and stiffness of recycled fibre-reinforced composite materials are reported [5,9]. The effect of reduced stiffness will be accounted for by the material invariants. The reduced strength can be included in the LP design space in the form of a set of linearized constraints [10]. Using these constraints (Fig. 2), the mechanical performance of a structure, e.g. buckling load can be optimized. As such an indirect link between specific energy required for recycling and mechanical performance of a part can be established. A designer can then choose to optimise structural performance for a fixed weight, or to minimise weight for minimum constraint on mechanical performance.

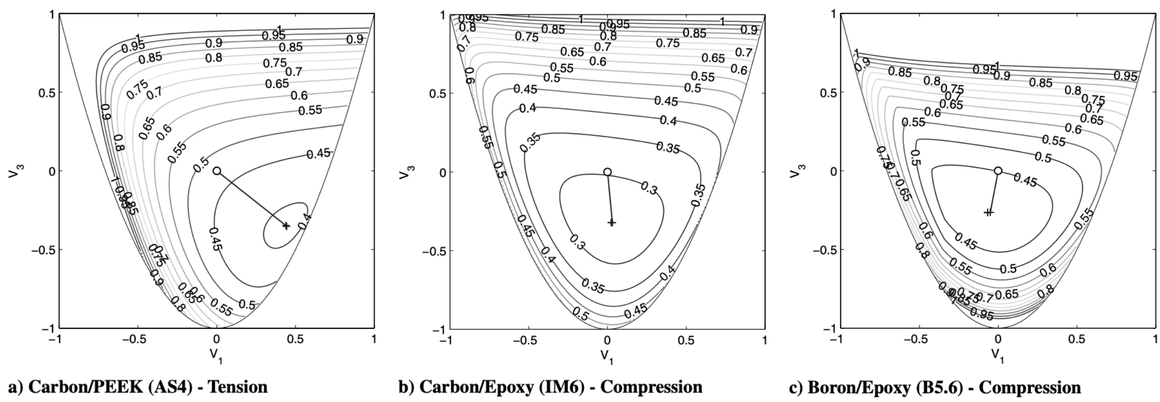


Figure 2. Strength constraints in LP space for different materials and loading [10].

## 3 OPTIMISATION METHOD FOR VARIABLE STIFFNESS LAMINATES

In section 2.2 it was established that the strength and stiffness of recycled composite laminates is expected to be lower than that of virgin material. Furthermore, it was expressed that the structural properties of the recycled material are likely to be a function of the specific energy required to recycle and then manufacture the part. Here the author proposes to compensate the loss in mechanical properties using variable stiffness (VS) laminate design.

### 3.1 Three-step optimization approach for variable stiffness laminates

The three-step method (Fig. 3) developed at the TU Delft [7] is well-suited to perform such a variable stiffness optimization. In the first step an optimized spatial distribution of lamination parameters (LP) is obtained. In the second step the optimised LP design is converted in to a stacking sequence design, resulting in a fibre angle distribution per layer in the laminate. In the third and final step, the fibre angle distributions per layer are converted into fibre paths, which are suitable for manufacturing using an automated fibre placement (AFP) machine.

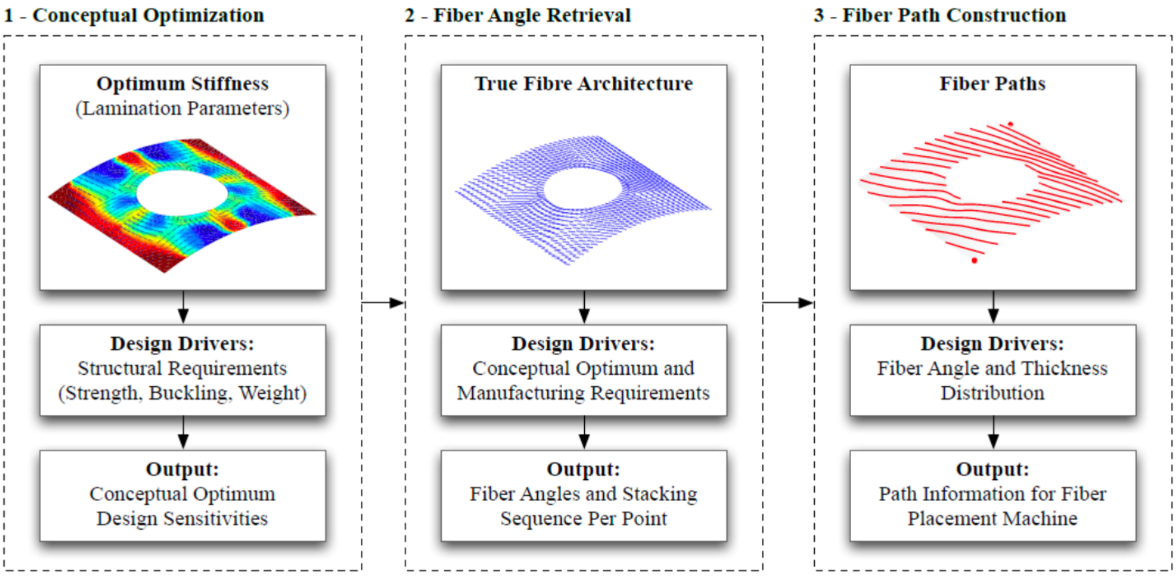


Figure 3. Three-step optimization method [7].

### 3.2 Straight fibre variable stiffness laminates

The straight fibre variable stiffness (SFVS) laminate design approach [11-14] simplifies VS laminate design (Fig. 4). The SFVS method divides a composite structure in a large number of design regions (Fig. 5). The stacking sequence of each of these design regions is optimised using lamination parameters (note that other optimisation methods are possible as well), after which a cellular automaton is used to generate patches that span multiple design regions, thus achieving continuity in the laminate. In 2019 the method already has been successfully demonstrated using a rectangular plate under uniform axial compression (Fig. 6). SFVS design was considered in this study because it is a versatile optimization method that can be combined with any manufacturing method.

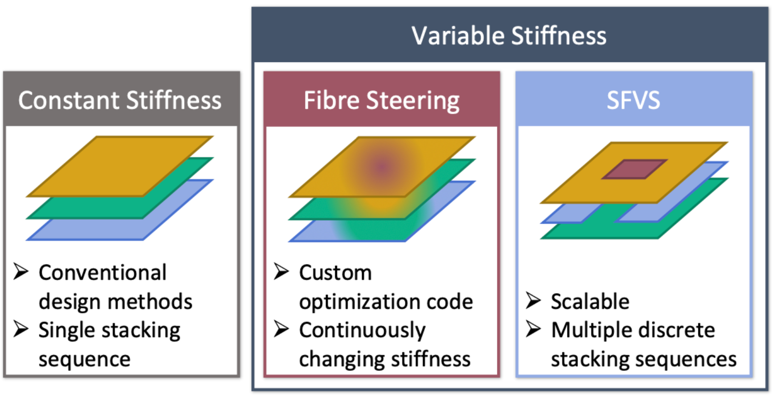


Figure 4. Straight fibre variable stiffness (SFVS) laminates [14].

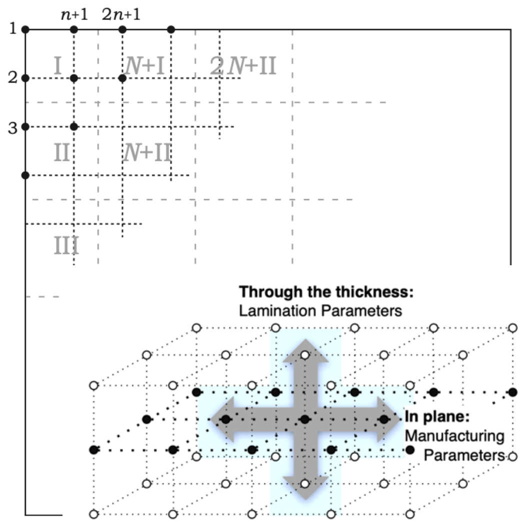


Figure 5. Straight fibre variable stiffness (SFVS) laminates with multiple design regions [12].

## 4 DEMONSTRATION ON UNIXAXIALLY COMPRESSED PLATE

### 4.1 Uniaxially compressed plate

The proposed method has been applied to a rectangular plate loaded in uniaxial compression (Fig. 6). The plate has a length of 600mm and a width of 400mm. The edges of the plate are simply supported. The compressive load on the short edges is applied uniformly and a clamped boundary condition is applied to the short edges, meaning that they cannot deform or rotate.

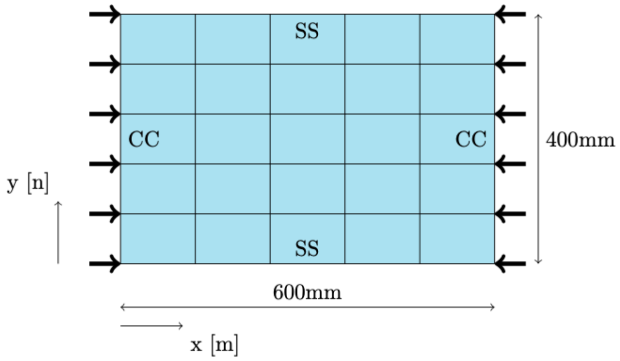


Figure 6. Uniaxially compressed plate with measurements and boundary conditions.

### 4.2 Material and processing properties

In the current work the following equations were used to determine the energy required to manufacture the composite component [8]:

$$\mathrm{Eb_C} = \mathrm{wf_{PM}} \bullet \mathrm{Eb_{PM}} + \mathrm{wf_{RF}} \bullet \mathrm{Eb_{RF}} \tag{2}$$

$$\mathrm{wf_{PM}} = \frac{\mathrm{m_{PM}}}{\mathrm{m_{RF}} + \mathrm{m_{PM}}} \tag{3}$$

$$\mathrm{wf_{RF}} = \frac{\mathrm{m_{RF}}}{\mathrm{m_{RF}} + \mathrm{m_{PM}}} \tag{4}$$

$$\mathrm{E_C} = \mathrm{E^{rw}}_\mathrm{C} + \mathrm{E^{m}}_\mathrm{C} = \mathrm{Eb_C} \bullet (\mathrm{m_{RF}} + \mathrm{m_{PM}}) + \mathrm{SEC_C} \bullet (\mathrm{m_{RF}} + \mathrm{m_{PM}}) \tag{5}$$

Where:

$Eb_c$: embodied energy of the composite (MJ/kg);
$wf_{PM}$: weight fraction of polymer matrix (-);
$Eb_{PM}$: emobodied energy of the polymer matrix (MJ/kg);
$wf_{RF}$: weight fraction of reinforcement (-);
$Eb_{RF}$: embodied energy of the reinforcement (MJ/kg);
$m_{PM}$: mass of the polymer matrix (kg);
$m_{RF}$: mass of the reinforcement (kg);
$E_C$: overall energy of the composite component (MJ);
$E^{rw}_C$: energy embedded in the composite raw materials (MJ);
$E^m_C$: energy needed to manufacture a composite component (MJ);
$SEC_C$: specific energy consumption of the manufacturing process (MJ/kg).

The properties of the materials that were considered in this work are given in table 1. The aluminium considered is a simple aluminium alloy which is fully recyclable. The values for the material have been estimated by the author, based on values found in literature. Composite A is a carbon fibre reinforced PEEK composite that is processed using laser assisted automated fibre placement and an autoclave [8]. Composite B is a glass fibre reinforced PEEK composite that is processed using hand lay-up followed by thermoforming. Both composites have the same fill percentage of 40%.

| Material | Young's modulus (GPa) | Tensile Strength (MPa) | $Eb_C$ [MJ/kg] | $SEC_C$ [MJ/kg] | $w_{RF}$ [%] | $w_{PM}$ [%] | E [MJ/kg] |
|---|---|---|---|---|---|---|---|
| *Aluminium* | 70.1 | 324 | - | 38.6 | - | - | 230 / 26.7[1] |
| *Composite A* | 30.2 | 276 | 392 | 600 | 40 | 60 | - |
| *Composite B* | 21.2 | 115 | 184.8 | 79 | 40 | 60 | - |

Table 1: Material properties used for current study. Note that these values have been estimated by the author, based on values found in literature, and that they may not be representative for actual materials. Here they are used for demonstration purposes only.

It is expected that an SFVS laminate with a larger number of design regions will require some more energy in the production process. Therefore, the following formula is proposed to account for this effect:

$$SEC_{SFVS} = SEC_{process} * n_{regions}^{1/a}. \tag{6}$$

Where $SEC_{SFVS}$ is the specific energy consumption of a production process ($SEC_{process}$) applied to an SFVS laminate and $n_{regions}$ is the number of design regions in the laminate; and $a$ is a scaling factor. Note that this equation is a simplification, overestimating the complexity of the laminate by equating it directly to the amount of design regions, rather than the amount of patches required to manufacture the laminate. Furthermore, please note, that this equation can also be applied to other production processes, for example additive manufacturing processes like 3D printing.

### 4.3 Results

A 2.0mm thick aluminium plate is taken as baseline design. The results for this plate are given in table 2. The energy to create aluminium from ore, as well as the energy in case recycled aluminium is used both are given.

The results for composite material A and B are given in tables 3 and 4 respectively. Note that the composite designs assume a layup of the following construction $[\pm\theta_1/\pm\theta_2/\pm\theta_3/\pm\theta_4/\pm\theta_5/\pm\theta_6/\pm\theta_7/\pm\theta_8]_s$.

[1] Recycled aluminium has a lower embodied energy. [15]

Note that the SFVS laminate design was obtained without considering the strength constraint of the material. The results reported in tables 3 and 4 are for the case that the thickness of the composite plates have been scaled to achieve the same buckling load as the aluminium plate. To this end the thickness of the lamina in the laminate has been considered to be a continues variable, and all lamina have been scaled by the same amount. It is noted that in more realistic cases the thickness of the laminate can only change in discrete steps.

The buckling loads in this study have been obtained using an in-house developed finite element code, which was also used for earlier work on the SFVS laminate technology. Note that, the value *a* in tables 3 and 4 refers to equation 6. Multiple values have been chosen, because at the moment of writing the correlation between $SEC_C$ and the amount of sections in a laminate is unknown.

| Buckling load [kN] | Weight [kg] | E [MJ] |
|---|---|---|
| 5.5351 | 1.296 | 298.08 / 34.99[2] |

Table 2: Results for baseline aluminium plate.

| Number of design regions [-] | Weight [kg] | E [MJ] | | | |
|---|---|---|---|---|---|
| | | $a = 2$ | $a = 4$ | $a = 6$ | $a = 8$ |
| 1 | 1.142 | 1133.00 | 1133.00 | 1133.00 | 1133.00 |
| 9 | 0.999 | 2190.03 | 1429.94 | 1256.22 | 1180.58 |
| *25* | 0.904 | 3065.95 | 1567.00 | 1281.68 | 1165.29 |
| 49 | 0.880 | 4040.53 | 1741.73 | 1354.84 | 1203.67 |
| 81 | 0.856 | 4960.45 | 1877.30 | 1404.59 | 1225.75 |
| 121 | 0.844 | 5900.10 | 2009.99 | 1456.79 | 1252.84 |
| 225 | 0.842 | 7909.80 | 2287.80 | 1577.01 | 1325.28 |

Table 3: Results for composite material A, PEEK-CF, automated fibre placement and autoclave.

| Number of design regions [-] | Weight [kg] | E [MJ] | | | |
|---|---|---|---|---|---|
| | | $a = 2$ | $a = 4$ | $a = 6$ | $a = 8$ |
| 1 | 1.593 | 420.22 | 420.22 | 420.22 | 420.22 |
| 9 | 1.393 | 587.77 | 448.18 | 416.28 | 402.39 |
| *25* | 1.261 | 730.93 | 455.66 | **403.27** | 381.89 |
| 49 | 1.227 | 905.45 | 483.30 | 412.25 | 384.49 |
| 81 | 1.194 | 1070.02 | 503.83 | 417.03 | **384.19** |
| 121 | 1.177 | 1240.24 | 525.86 | 424.27 | 386.82 |
| 225 | 1.174 | 1609.99 | 577.57 | 447.05 | 400.82 |

Table 4: Results for composite material B, PEEK-GF, hand layup and thermoforming.

[2] Recycled aluminium has a lower embodied energy. [15]

## 5 DISCUSSION AND OUTLOOK

In this paper a very simplified approach has been presented to include a life cycle metric in the design process of a recycled fibre-reinforced composite part. Below the obtained results are discussed, after which an outlook is given for further research on the subject.

### 5.1 Discussion

Before discussing the results it must be noted, that the values used to generate the results for this study have been chosen for demonstration purposes only. They have been derived from values that can be found in literature, but they are not representative for any particular existing manufacturing process or material system. Instead, they are used to outline possible trends, and they should be seen as an invitation to the reader to generate such values for existing processes. Furthermore, please note that the thickness of the plate has been treated as a continuous variable in this study, whereas in reality there would be discrete jumps in thickness.

The first thing that stands out from comparing the results in tables 2, 3 and 4, is that the energy required to manufacture the aluminium plate is lower than for either material system for the composite plate in baseline configuration, i.e. with one design region. At the same time, the weight for composite A, 1.142kg, is found to be lower than the aluminium plate, 1.296kg, and for composite B higher, 1.593kg. For both composite plates the weight of the plate can be seen to converge to a minimum value for an increasing number of sections in the laminate.The lowest values found are 0.842kg for composite material A and 1.174kg for composite material B, respectively 35.02% and 9.38% lighter than the aluminium plate.

For composite material A increasing the number of sections in the laminate results in an increase in the energy required to manufacture the plate. This was expected, as the assumption has been made that a more complex laminate design will require more energy to manufacture. It will depend on the final application of the plate to determine whether the increase in required energy can somehow be offset w.r.t. the weight saved by using the material combined with the given number of sections in the laminate.

For composite material B it can be seen that for the values $a = 6$ and $a = 8$ there occurs a minimum in the amount of energy required to manufacture the plate for an increasing amount of sections in the SFVS laminate. This can be explained by the fact that the reduction in material required to manufacture the plate offsets the increased amount of energy required for the production process. This is a clear indication that there is an incentive to make the production process as efficient as possible.

Overall, the results show that it is possible to compensate for a reduction in material performance, typically associated with recycled composite materials compared to virgin composite materials and/or lesser energy intensive production methods, by using straight fibre variable stiffness laminate design. Especially when the embodied energy in the composite material is larger than the specific energy consumption of the manufacturing process, as is the case for composite material B, optimisation of the structure may also lead to a reduced amount of energy required to manufacture a part.

Another important result of this preliminary study is that choice for recycled fibre reinforced composite materials over aluminium parts is to be carefully considered should life cycle impact benefit of light-weighting aircraft structures become less dominant in the future.

### 5.2 Outlook

The work presented here is only a preliminary study, in which only the energy required to manufacture a part has been considered. The indirect link between the energy requirement and strength constraints has not been used yet in obtaining the results and no link has been established yet between the increase in energy required by the production process if the complexity of the composite design increases. All these points will be addressed in future work by the author.

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