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DOI
10.2514/6.2024-0835

Publication date
2024

Document Version
Final published version

Published in
Proceedings of the AIAA SCITECH 2024 Forum

AIAA SciTech Forum
8-12 January 2024, Orlando, FL
AIAA SCITECH 2024 Forum
10.2514/6.2024-0835

Exploring the potential of variable stiffness design in reducing the life-cycle impact of composite aircraft parts

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In 2022 Airbus and Boeing combined delivered 1203 commercial aircraft. With an annual predicted growth of 4.3% for the coming 20 years there is an urgent need for end of life solutions that go beyond down-cycling of parts that cannot be reused. Especially carbon fibre reinforced composites are hard to recycle, and attempts to deliver recyclable short fibre reinforced thermoplastic materials see a reduction in specific properties. This is a problem because, the life cycle impact of an aircraft part is predominantly determined by its weight, which drives cumulative CO_2-emissions over its lifetime. The transition to renewable energy sources by the aviation sector has the potential to change this relationship drastically. Therefore, it is necessary to begin developing methods to account for life cycle impact already at the start of the mechanical design of an aircraft part. This study proposes to apply variable stiffness laminate design to compensate for relatively lower mechanical performance of a recyclable short fibre reinforced composite laminate, with the objective of an overal better life cycle performance of the composite part. This approach is demonstrated using the example of a rectangular plate under uniaxial compression on board of an ATR72. The results show the impact of weight-optimisation on the cumulative CO_2-emissions for the life span of the aircraft. Two different energy sources are considered: the aircraft powered by conventional jet fuel, and the aircraft powered by hydrogen which has been generated using non-fossil energy sources. The results furthermore clearly show that moving from conventional to renewable energy sources, reduces the impact of part-weight on the accumulated CO_2-emissions very significantly, bringing recycling considerations more into focus, especially for parts which require regular replacement during the lifespan of the aircraft, for example hydrogen storage tanks.

I. Nomenclature

a	=	scaling factor (-)
b	=	scaling factor (-)
Eb_c	=	embodied energy of the composite (MJ/kg)
Eb_{PM}	=	emobodied energy of the polymer matrix (MJ/kg)
Eb_{RF}	=	emobodied energy of reinforcement (MJ/kg)
E_C	=	overall energy of the composite component (MJ)
$E^m{}_C$	=	energy needed to manufacture a composite component (MJ)
E_C^{rw}	=	energy embedded in the composite raw materials (MJ)
LCA	=	Life Cycle Assessment
m_{PM}	=	mass of the polymer matrix (kg)
m_{RF}	=	mass of the reinforcement (kg)
$n_{regions}$	=	number of regions in the laminate (-)
PVS	=	Patched Variable Stiffness
SEC_C	=	specific energy consumption of the manufacturing process (MJ/kg)
VS	=	Variable Stiffness
wf_{PM}	=	weight fraction of polymer matrix (-)
wf_{RF}	=	weight fraction of reinforcement (-)
W_r	=	weight reduction of part (kg)
wf_{RF}	=	typical in-service weight of aircraft (kg)

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κ = In-plane curvature (m^{-1})

II. Introduction

The driving factor in the design of aircraft structures is weight, because reduced weight leads to reduced fuel consumption, and because weight reduction in one location of the aircraft will lead to potential weight reduction elsewhere in the aircraft. The latter is also known as the snowball effect. The resulting desire for light-weighting has driven the aviation industry to use materials with ever higher weight-specific properties, for example carbon fibre reinforced composites (CFRP).

A main drawback of CFRP is, that to date, there are known ways to recycle them at a an industrial scale. The necessity for recycling can be illustrated by the volume of the commercial aircraft market. Airbus delivered 661 new commercial aircraft in the year 2022. [1] Boeing reported the delivery of 542 new commercial aircraft [2] in the same year. Over the next 20 years air transport is predicted to grow with 4.3% per annum. [3]. Considering an average service life of 20 to 30 years for a commercial aircraft, this means that towards the end of this century there will be a lot of old aircraft parts that cannot be recycled. A solution to this problem is therefore urgently needed.

Short fibre reinforced thermoplastic composite materials that can be recycled multiple times [4] could provide a solution to the problem sketched above. However, their specific properties are reported to be lower than those of virgin composite materials. Thus, the weight of an aircraft part made from such recycled material is likely to be higher than for a conventional CFRP part. Within the prevailing paradigm that most of the life cycle impact comes from CO_2-emissions during the operational phase of the aircraft, this would make recycled CFRP parts a non-viable solution.

In this work, the author wants to challenge this paradigm, arguing that since aviation industry is striving towards climate neutrality by the year 2050 [5], the accumulated CO_2-emissions over the lifespan an aircraft part will significantly reduce in the case renewable energy sources are used. This will require a change of thinking in the type of materials used for aircraft, potentially favouring materials with a lower life cycle impact. Of course the energy transition in aviation has not happened yet, but it is necessary to think ahead for when it will have.

The objective of the work presented is to investigate how the mechanical performance of fibre reinforced composite materials can be linked to metrics determining the life cycle impact of an aircraft part. In section III an attempt is made to make an initial version of this connection. The author chooses variable stiffness (VS) laminate design as potential solution to compensate for reduced mechanical performance by means of structural optimisation, as will be explained in section III.D. Preliminary results are given in section V, after which the preview of possible conclusions is given in section VI, where it should be noted that the presented work are first steps to include life cycle impact in the structural design of composite structures for aviation.

III. Mechanical Performance as Function of Life Cycle Impact

There are many metrics that are used to perform the life cycle assessment (LCA) of an aircraft or a component thereof. Most LCA approaches rely heavily on data-bases that link specific materials and manufacturing processes to these metrics. [6] The current work is a first step by the author to develop a more comprehensive approach for laminated fibre reinforced composite structures to include life cycle impact from the very first mechanical design. In the presented work the amount of energy required to manufacture a recyclable short fibre reinforced thermoplastic aerospace part was estimated, which was then linked to the associated CO_2-emissions. Here the implicit assumption by the author was made that the specific strength and stiffness of the material will be better if a more energy intensive manufacturing method or material system are used.

For the purpose of demonstration it was then assumed that the composite part was part of an ATR72, to give an estimate of the accumulated CO_2-emissions for the lifespan of the aircraft. Two alternative fuel sources for the aircraft were considered: Jet A and hydrogen, generated using non-fossil energy sources.

A. Energy Required to Manufacture

The method proposed by Lunetto *et al.* [7] was used in this paper. For this method the energy required to manufacture the composite component is calculated using the following equations:

$$Eb_c = wf_{PM} \cdot EbPM + wf_{RF} \cdot Eb_{RF} \quad (1)$$

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.

Material	Young's Modulus (GPa)	Eb_C (MJ/kg)	SEC_C (MJ/kg)	W_{RF} (%)	W_{PM} (%)	E (MJ/kg)
Aluminium	70.1	-	38.6	-	-	230
Composite A	30.2	392	600	40	60	
Composite B	21.2	184.8	79	40	60	

$$wf_{PM} = \frac{m_{PM}}{m_{RF} + m_{PM}} \tag{2}$$

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

$$E_c = E_C^{rw} + E_C^m = Eb_C \cdot (m_{RF} + m_{PM}) + SEC_C \cdot (m_{RF} + m_{PM}) \tag{4}$$

Next to an aluminium baseline design, two fictitious material systems were considered for the purpose of demonstration, see table 1. It can be noted that the stiffness values for the two composite materials are lower than could be expected for a non-recyclable composite with continuous fibres. This will lead to heavier designs for structures of which the design is dominated by material stiffness, like e.g. panels under compression.

B. Energy Required During Aircraft Lifespan

The propulsive power of an aircraft is given in Eq. 5.

$$P_p = \frac{W}{L/D} \tag{5}$$

From this relation it can be seen that the required propulsive power is directly related to the weight of the aircraft. Therefore, even small weight reductions can have a large effect on the cumulative energy required during the lifespan of the aircraft.

An energy reduction ratio is introduced (Eq. 6), that was used to estimate the reduction in energy requirement due to achieved weight reduction.

$$r_r = \frac{W_r}{W_S} \tag{6}$$

Where W_r is the weight reduction of the part and W_S is the typical in-service weight of the aircraft.

C. Greenhouse Gas Emissions

The amount of greenhouse of CO_2 or equivalent greenhouse gasses that are emitted to the atmosphere depends on the energy source that is used. As can be seen from table 2 the differences are significant, especially between fossil and non-fossil power sources. In this work 780g CO_2-eq/kWh was assumed for the worst available power mix in terms of emissions, like for example available in Poland [8]. The cleanest possible power-mix that seems possible is $10 - -100$g CO_2-eq/kWh. For this paper it was assumed that for a hydrogen-powered aircraft this clean power mix would be used to generate the hydrogen.

D. Variable Stiffness Laminates

In this work the author proposes to compensate the reduced mechanical performance by applying a variable stiffness (VS) design approach. In variable stiffness laminates the fibre angle orientation is spatially varied within the laminate, which can be used to increase for example the buckling load of a part. In this study two different types of variable stiffness laminates will be considered: laminates with steered fibres and patched laminates with straight fibres.

Table 2 Greenhouse gas emissions per energy source, modified from [9] in [g CO_2-eq/kWh]

Fossil	Oil	733
	Jet A (estimated value)	523
	Natural gas	499
Non-fossil	Photovoltaic	300
	Onshore Wind	124
	Geothermal	78
	Tidal	50
	Wave	50
	Nuclear	24
	Offshore Wind	9

E. Three-Step Design Approach

The three-step method (Fig. 1) developed at the TU Delft [10] is well-suited to perform such a variable stiffness optimization. In the first step an optimized spatial distribution of lamination parameters (LP) is obtained. Any strength and stiffness constraints can be taken into consideration in the LP-space. 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. Typically, this results in a fibre-steered design.

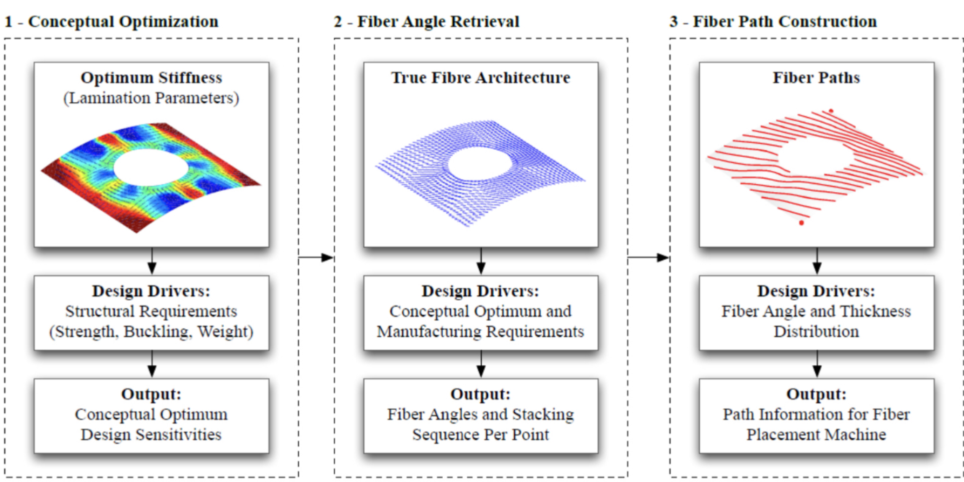

Fig. 1 Three-step optimization method for variable stiffness laminates [10]

F. Patched Variable Stiffness Laminates

The patched variable stiffness (PVS) laminate design approach [11–14] simplifies VS laminate design (Fig.2). The PVS method divides a composite structure in a large number of design regions. 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. 3). PVS design was considered in this study because it is a versatile optimization method that can be combined with any manufacturing method.

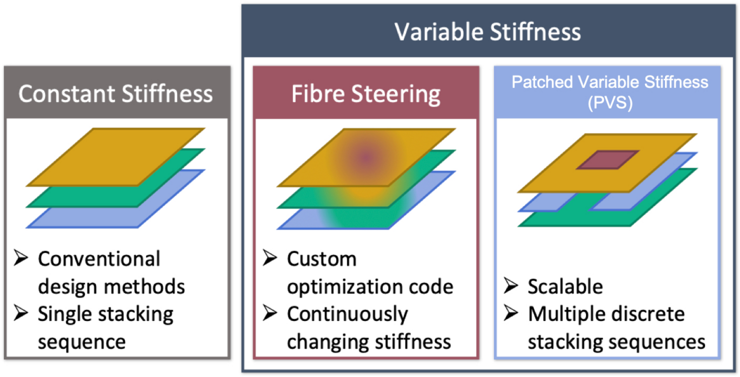

Fig. 2 Patched variable stiffness (PVS) laminates [14]

Table 3 Estimated use data for ATR72

Service life	30	years
Operational per year	350	days
Flights per day	10	[−]
Average flight duration	2	hours
Typical in-service weight	13600	kg
Fuel rate	650	$\frac{kg}{hr}$

IV. Case Study: Composite Panel on Board of ATR72

One of the underpinning assumptions of the current work is that aviation will see a transition to using energy sources that do not require fossil fuels. An example of this is hydrogen-powered aviation. In March 2023 a first successful flight of a regional airliner has been performed by the company Universal Hydrogen [15] using an ATR72. Therefore, in this work an ATR72 is used as reference aircraft. The data that was used to make the estimates presented in the paper are given in table 3.

Using this data, and that of table 2 it can be estimated that during its lifespan an ATR72 will require $1.63 \cdot 10^9$ kWh of energy. Using Jet A as fuel this would be equivalent to $435 \cdot 10^3$ tonnes CO_2-emissions. Using hydrogen as fuel this would be between $32.7 \cdot 10^3$ and $163 \cdot 10^3$ tonnes CO_2-emissions, assuming all other parameters of the aircraft remain unchanged.

Using equation 6 this would yield a reduction of 31.96 tonnes CO_2-emissions per kg of saved weight for the conventional aircraft and in the most optimistic scenario 2.403 tonnes CO_2-emissions per kg of saved weight for the hydrogen-powered aircraft, both measured over a 30 year life span.

For the sake of argument here it is assumed that somewhere in the ATR72 structure there is a unixially compressed plate made out of aluminium, for which replacement is being considered using one of the two material systems presented in table 1.

A. Uniaxially Compressed Plate

The proposed method will be applied to a rectangular plate loaded in uniaxial compression (Fig. 3). 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.

Note that for life cycle analysis (LCA) it is atypical to perform such analysis on just a part. Typically, the entire system is considered. In this paper an attempt was made to combine the two worlds, making LCA a more manageable concept for aerospace design studies.

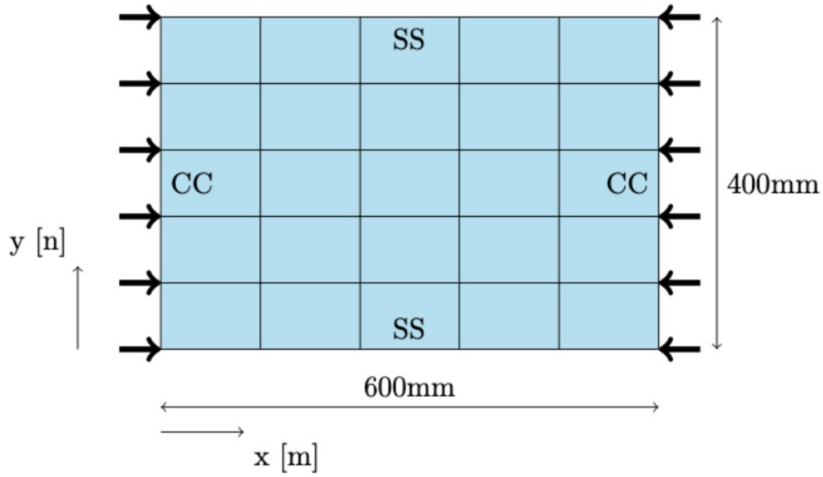

Fig. 3 Uniaxially compressed plate with measurements and boundary conditions.

Table 4 Results for the baseline aluminium plate.

Buckling load (kN)	Weight (kg)	E (MJ)
5.5351	1.296	298.08

B. Energy Required to Manufacture

As relation between the curvature of the steered fibres and the energy required to manufacture the VS laminate the following relationship was used:

$$SEC_{VS} = SEC_C \cdot e^{\frac{\kappa}{a}} \tag{7}$$

Similarly a method to relate the complexity of the PVS laminate to the required energy to manufacture it, is currently under development. To demonstrate the method, the following equation was used:

$$SEC_{PVS} = SEC_C \cdot n_{regions}^{\frac{1}{b}} \tag{8}$$

For both equations the logic was that with increasing curvature respectively complexity of the laminate the energy required to manufacture it will scale. It is expected that the number of designed regions will play a role in this scaling. Therefore, these equations is proposed as first attempt to capture the correlation. Here a and b are scaling factors.

V. Results

A. Energy required for Manufacturing

The properties of the materials that were considered for this paper 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 [7]. 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%.

A 2.0mm thick aluminium plate was taken as baseline design. The results for this plate are given in table 4. The energy to create aluminium from ore, as well as the energy in case recycled aluminium is used both are given.

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 PVS laminate technology. Note that, the values for a and b in tables 6 and 7 refer to Eq. 7 and 8. Multiple values have been chosen, because at the moment of writing the correlation between SEC_C and the curvature respectively the amount of sections in a laminate is unknown. Note, that for the fibre-steered design EC_C

Table 5 VS results for composite material A, PEEK-CF, automated fibre placement and autoclave.

Max. curvature (m^{-1})	Weight (kg)	E (MJ)			
		$a = 1$	$a = 10$	$a = 100$	$a = 1000$
0	1.142	1133.00	1133.00	1133.00	1133.00
1.00	1.097	2218.27	1156.96	1094.38	1088.43
1.25	1.090	2710.33	1168.52	1089.65	1082.24
2.50	1.075	8277.50	1249.35	1082.52	1067.81
5.00	1.046	93598.3	1445.45	1070.31	1041.27
10.0	1.021	13493274	2065.37	1077.22	1018.95
12.5	1.016	163601883	2526.34	1089.19	1015.68
25.0	1.009	$4.3203 \cdot 10^{13}$	7771.48	1172.98	1016.34
50.0	1.009	$3.1391 \cdot 10^{24}$	90252.6	1393.78	1032.07

Table 6 PVS results for composite material A, PEEK-CF, automated fibre placement and autoclave.

$n_{regions}$ (-)	Weight (kg)	E (MJ)			
		$b = 2$	$b = 4$	$b = 6$	$b = 8$
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

clearly shows an optimum for $a = 10$ and $a = 100$. The results for $a = 1000$ are deemed unrealistic, because they imply that EC_C would decrease with increasing curvature.

B. Life Cycle Greenhouse Gas Emissions
For this section scaling factors a and b are chosen to be 100 and 8 respectively. The results that were obtained for these values are given in table 8 for the lightest design. In this table the cleanest energy mix for the non-fossil production of the plate and of hydrogen is considered.

VI. Discussion

A. Caveats
Before discussing the first results it must be noted, that the values used to generate the results for this study have been chosen for demonstration purposes only, and that many assumptions were made obtaining them. 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. Also, a conscious choice has been made only to compare recyclable material systems. Having that said, the methodology can be expanded to include other material systems as

Table 7 PVS results for composite material B, PEEK-GF, hand layup and thermoforming.

$n_{regions}$ (-)	Weight (kg)	E (MJ)			
		$b=2$	$b=4$	$b=6$	$b=8$
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 8 Emissions for different designs, considering most energy efficient manufacturing

		Aluminium	**VS Mat A**	**PVS Mat A**	**PVS Mat B**
W_r	[kg]	-	0.29	0.45	0.12
E	[MJ]	298.08	1393.78	1325.28	400.82
CO_2-emissions fossil energy mix	[kg]	64.58	301.99	287.14	86.84
CO_2-emissions non-fossil energy mix	[kg]	8.28	38.72	36.81	11.13
CO_2-emission reduction (fuel: Jet A)	[kg/year]	-	9170.67	14508.25	3883.78
CO_2-emission reduction (fuel: hydrogen)	[kg/year]	-	344.76	545.42	146.01
Break even time (fuel: Jet A)	[days]	-	12.02	7.22	8.16
Break even time (fuel: hydrogen)	[days]	-	319.71	192.16	217.10

well.

Last, but not least, in terms of LCA it is very atypical to consider the life cycle performance of just one part, rather than the entire system. Here an attempt was made to bridge this gap between aerospace design and LCA.

B. Life Cycle Emissions

The first thing that stands out from table 8 is that no matter the energy source used to power the aircraft, light-weighting has a significant impact on the life cycle CO_2-emissions of a composite aircraft part. However, the impact becomes smaller when using non-fossil energy sources to power an aircraft.

Looking at the break even point, when the CO_2-emissions of production have been compensated by the CO_2-emission during operation, the differences between fossil and non-fossil energy sources are striking. Nevertheless, even is the most optimistic scenario of the cases that have been considered in this paper, the break even point is only 319.71 days in service. This suggests that the proposed methodology is especially interesting for parts that require frequent replacement.

The method that has been presented in this paper could be used in selecting material systems and production processes bearing in mind their impact on overall life cycle performance of the aircraft. Alternatively, it could be argued to be an argument in favour of improving the mechanical performance of recycle-able material systems.

Additionally, the author would like to remark here, that the results clearly show that moving towards battery-electric aviation is not a good idea in terms of CO_2-emissions, because even for non-fossil energy sources more weight will lead to more CO_2-emissions.

C. Manufacturing Optimisation

Zooming in on the design of the panels themselves, the first thing that stands out is that it is possible to optimise the embodied energy of the part using variable stiffness design. The fibre steered VS design, for which only results could be obtained for material system A, and the PVS shown the same trends.

Comparing the results in tables 4, 6 and 7, 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. Similarly, for the VS design, it can be seen that increasing the steering curvature, improves the mechanical, making it possible to save on the overall energy requirement of the composite part.

For composite material B it can be seen that for the values $b = 6$ and $b = 8$ there occurs a minimum in the amount of energy required to manufacture the plate for an increasing amount of sections in the PVS 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.

D. Outlook

Overall, these first 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 an attractive proposition for parts with a short lifespan, requiring frequent replacement. Here for example hydrogen storage tanks would come to mind.

Moving towards a non-fossil energy mix, the impact of light-weighting on the greenhouse gas emissions of an aircraft during its lifespan should be considered more carefully.

In follow-up realistic material data and aircraft data shall be considered.

Acknowledgments

The author would like to thank Roeland De Breuker for pushing him to expand his work into new fields of research. Furthermore, the author would like to thank Natalia Gomes de Paula and Deniz Gülmez for the insightful and inspiring conversations on the subject of life cycle assessment and waste reduction.

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