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Composite engine thrust frame design and manufacturing using fibre steering optimization for launcher structures

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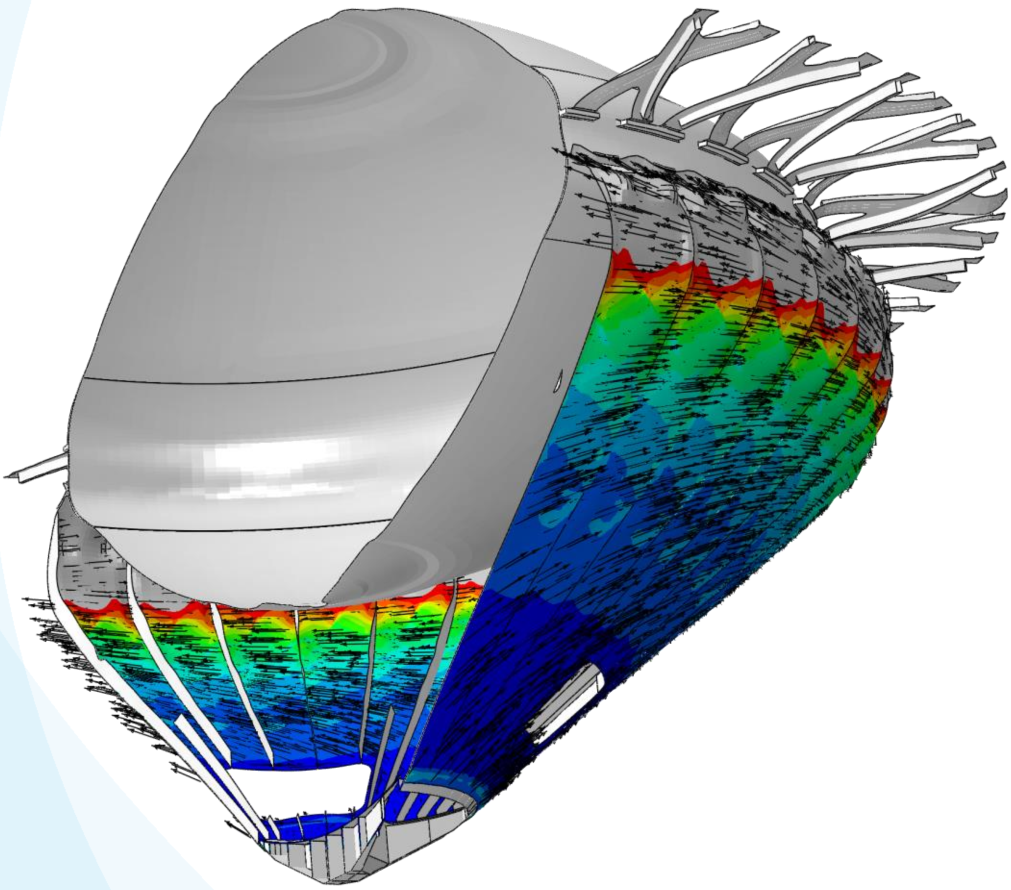

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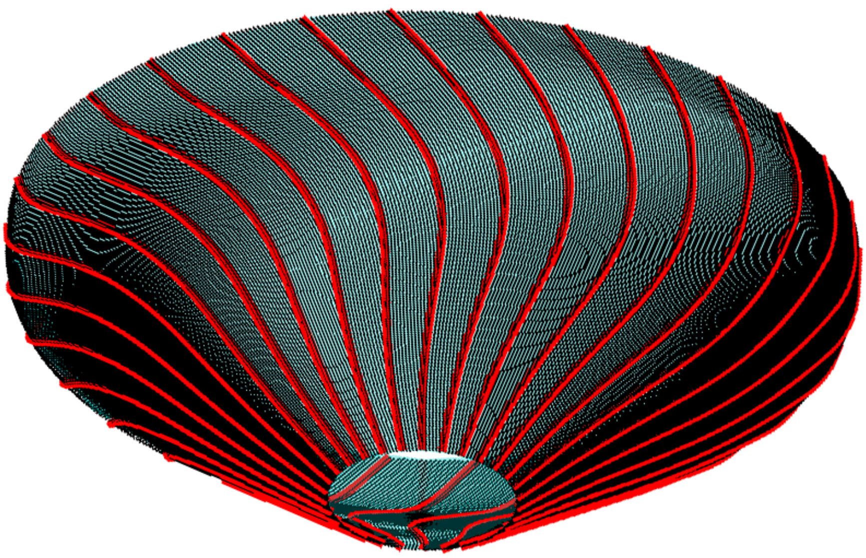

Thrust frame design with steered fibre paths as part of launcher structures

Problem area

New space launcher systems from ESA will enter a very competitive commercial launcher market. New entrants to this market have reduced the launch price per unit mass payload by half (50%). As a consequence a key requirement for the development of new launchers is reduced recurring production costs and increased performance.
A part of the space launcher is the Engine Thrust Frame (ETF), also known as the ViTF (Vinci Thrust Frame). This research was done under lead of Airbus Defense and Space Netherlands and funded by ESA. In line with the launcher's key requirements the main goal of this research is to save recurring production costs, lower the weight and keep the stiffness requirements of the composite ViTF structure using different innovative design and stiffening techniques, such as fibre steering.

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Description of work

The Carbon Fibre Reinforced Plastic (CFRP) full scale reference thrust frame was used as a starting point. Design and optimization of the thrust frame composite layup using the fibre steering method is performed to reduce weight and meet the mechanical requirements. This was followed by detailed analyses and evaluation of the design. For testing purposes the full scale design was scaled down to 1:3 scale. This 1:3 design is manufactured and tested.

Results and conclusions

The optimisation of the full-scale thrust frame design and 1:3 scaled version leads to a significant reduction in weight of 15% compared to the Carbon Fibre Reinforced Plastic (CFRP) reference design. This is achieved by reduction of the amount of blade stiffeners and introduction of the automated fibre steering which results in a more optimal design. The requirements for safety, strength and stiffness are still met with the new design. The optimisation efforts resulted in a design that reached ultimate load without failure and buckling.

Applicability

The tools and methods developed enable next generation composite structures using laminate optimization and fibre steering.

GENERAL NOTE
This report is based on a presentation held at the Sampe conference on the 29-30 September 2021 in Baden, Switzerland

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Summary

New space launcher systems from ESA will enter a very competitive commercial launcher market. New entrants to this market have reduced the launch price per unit mass payload by half (50%). As a consequence a key requirement for the development of new launchers is reduced recurring production costs and increased performance.
A part of the space launcher is the Engine Thrust Frame (ETF), also known as the ViTF (Vinci Thrust Frame). This research was done under lead of Airbus Defense and Space Netherlands and funded by ESA. In line with the launcher's key requirements the main goal of this research is to save recurring production costs, lower the weight and keep the stiffness requirements of the composite ViTF structure using different innovative design and stiffening techniques, such as fibre steering.

The Carbon Fibre Reinforced Plastic (CFRP) full scale reference thrust frame was used as a starting point. Design and optimization of the thrust frame composite layup using the fibre steering method is performed to reduce weight and meet the mechanical requirements. This was followed by detailed analyses and evaluation of the design. For testing purposes the full scale design was scaled down to 1:3 scale. This 1:3 design is manufactured and tested.

The optimisation of the full-scale thrust frame design and 1:3 scaled version leads to a significant reduction in weight of 15% compared to the Carbon Fibre Reinforced Plastic (CFRP) reference design. This is achieved by reduction of the amount of blade stiffeners and introduction of the automated fibre steering which results in a more optimal design. The requirements for safety, strength and stiffness are still met with the new design. The optimisation efforts resulted in a design that reached ultimate load without failure and buckling.

The tools and methods developed enable next generation composite structures using laminate optimization and fibre steering.

Contents

Abbreviations

ACRONYM	DESCRIPTION
AFP	Automated Fibre Placement
CFRP	Carbon Fibre Reinforced Plastic
CS	Constant Stiffness composite laminates
ETF	Engine Thrust Frame
ESA	European Space Agency
FE	Finite Element
FEM	Finite Element Method
FLPP	Future Launchers Preparatory Programme
IM7	Carbon Fibre type
NLP	NonLinear Programming
NLR	Royal NLR - Netherlands Aerospace Centre
NSP	Non Smooth Problem
TRL	Technology Readiness Level

1 Abstract

Key words: composite, fibre steering, space, engine thrust frame, design method, optimization

Fibre steering for Carbon Fibre Reinforced Plastic (CFRP) design has been investigated for several decades. It has been shown that performance improvements using fibre steering technology, also known as variable stiffness, can be achieved and potentially be translated into structural weight reduction. However, actual application of this technology has been limited. In this paper the fibre steering design and manufacturing is presented with an application to a launcher structure as part of a technology development program in the frame of the ESA's Future Launchers Preparatory Programme (FLPP) led by Airbus Defence and Space Netherlands. This launcher structure is the Engine Thrust Frame (ETF) which is the subject of design, optimization and manufacturing. The main goals of the development program are to save recurring production costs, lower the weight and comply with the stiffness and strength requirements of the composite ETF structure innovative design. The Automatic Fibre Placement (AFP) technique is used as manufacturing process.

The present paper describes the composite design optimization process using fibre steering optimization methods applied to the ETF with multiple loadcases. The approach uses in-loop finite element calculations and control points interpolation of the steered-ply orientation. This is followed by the translation to the actual fibre paths for AFP manufacturing using the in-house developed PathFinder tool. Optimisation of the full-scale design by reduction of the number of blade stiffeners and introduction of the automated fibre steering and smart overlapping technology, led to a significant reduction in expected recurring production costs as well as a weight reduction of 15% compared to the CFRP reference design while satisfying the strength and stiffness requirements. The optimisation efforts resulted in a design with two critical failure modes above the ultimate load, i.e. fibre compression in the stiffener run-out and local buckling of a stiffener. A 1:3 scaled design of the ETF with a diameter of approximately 1.5 meter was successfully manufactured and tested at NLR.

2 Introduction

2.1 Application

In space launcher structures the loads from the engine to the upper stage are transferred by the so-called conical shaped Engine Thrust Frame (ETF). The location of the frame in the upper stage of the Ariane 6 launch vehicle is illustrated in Figure 1. The engine thrust frame has to be strong enough to transfer the engine loads as well as loads related to equipment mounted on the frame and withstand cryogenic temperatures in the upper region. In addition, the thrust frame has to provide enough stiffness for the stability of the upper stage during launch.

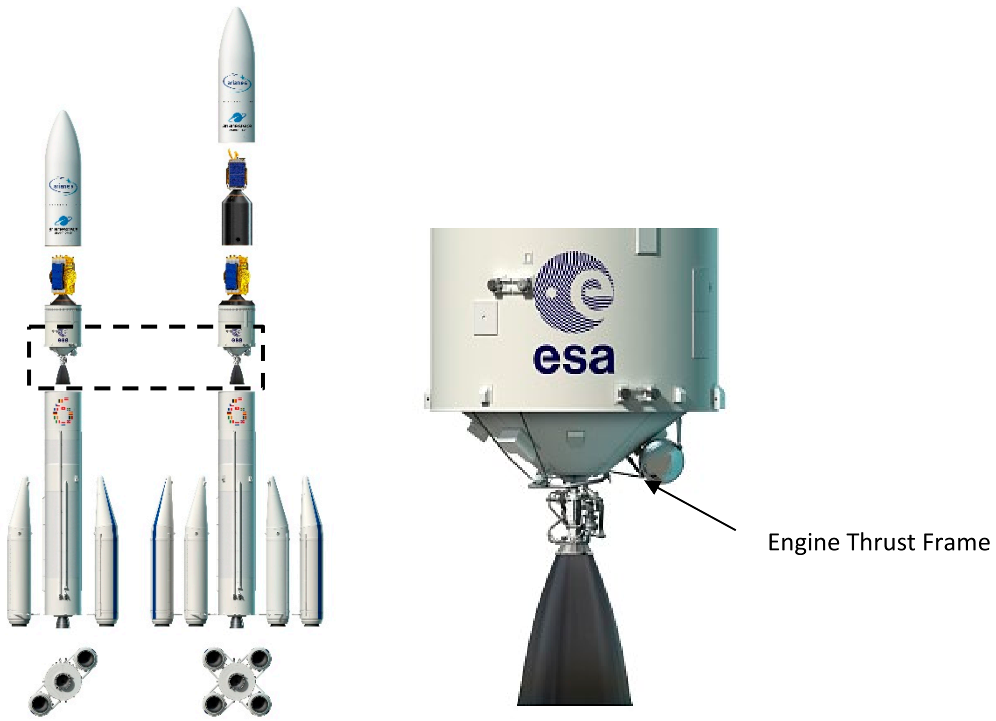

Figure 1: Launcher configurations and location of the engine thrust frame (source: ESA)

The engine thrust frame currently is constructed of aluminium and for future developments it is believed performance and/or weight improvements can be achieved by replacing the aluminium design by a CFRP design including fibre steering technology [1] and [2]. Important design metrics are reduction of mass and cost while maintaining the overall stiffness of the engine frame.

The engine frame has a conical shape with a transition to a cylindrical shape. The engine and engine gimbal is mounted to the cone cap which is connected to the conical part of the engine frame. A connection to the liquid oxygen tank is present at the top of the cylindrical part. In the current aluminium design the conical and cylindrical shapes consist of separate parts connected by a ring. For the CFRP design both shapes are combined into one part. In order to achieve a Technology Readiness Level (TRL) between 5 and 6 a demonstrator of the ETF is designed, manufactured and tested. In addition, coupon and panel tests have been performed to validate the design methodology and gain confidence in the simulation of the proposed design. The demonstrator is a scale 1:3 version of the full scale design. A detailed description of the 1:3 scale version is outside the scope of this paper and the focus lies on the CFRP design using fibre steering.

2.2 Fibre steering composite design

The basis for improved mechanical performance of fibre steered composite structures comes from optimized use of the anisotropic properties of the laminate material. The use of traditional laminates with only unidirectional plies, illustrated in Figure 2, poses a strong limitation on the possibilities for laminate design. Allowing the use of variable stiffness laminates with arbitrary angles over the entire laminae the design space is significantly increased.

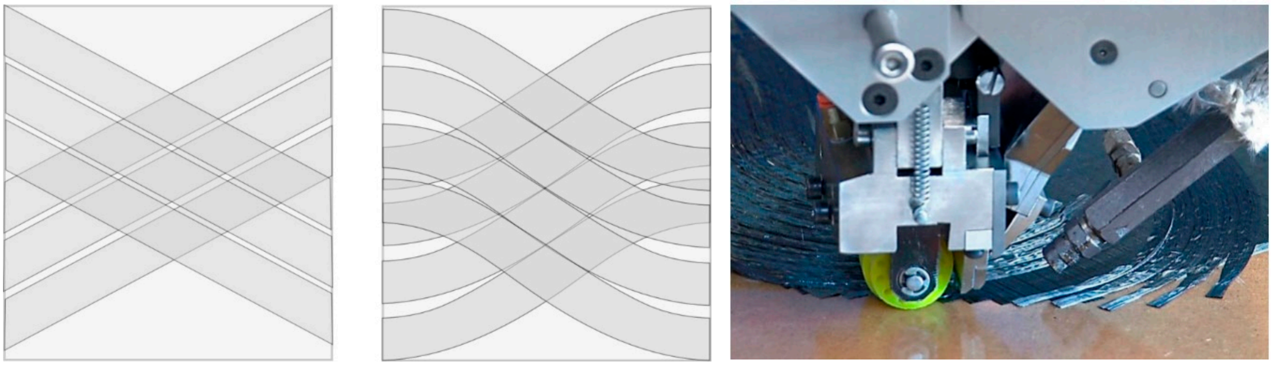

Figure 2: Illustration of composite fibre direction for a conventional constant stiffness laminate (left) and variable stiffness laminae (middle). On the right the manufacturing of fibre steered laminates using the fibre placement manufacturing at NLR

Variable stiffness laminates can be optimized for various applications such as bearing bypass, load changes, buckling and tailoring elastic properties (morphing structures) [3] and [4]. The focus in this paper lies on stiffness, weight and strength optimization of the ETF structure.

In literature fibre steering or variable stiffness CFRP design and optimization problems are addressed in various ways. This has been shown in literature for optimization of e.g. for buckling problems, through direct variation of local fibre orientations; a second approach is defining the fibre orientations on the basis of principal strains for strain resistance optimization problems. The controlled variable stiffness optimization has been extensively investigated by Gürdal and co-workers [5][6][7] and [8] showing good improvements compared to conventional laminates.

For a simple research demonstration cases such as buckling of a flat plate, a significant buckling load improvement ranging from 35 – 67% is shown in literature by using variable stiffness (VS) laminates compared to constant stiffness (CS) laminates. In research by Lund et. al. [9] the discrete material optimization (DMO) is used for the flat plate buckling case showing a 35% improvement in linear buckling load. In work by Setoodeh *et al*. [10] a generalized reciprocal approximation approach is used to define the critical buckling load using first order Taylor series expansion. In the technical report by Luraghi [11] a NURBS base-curve approach is used that uses a central curve from which parallel derivative curves are created. In the present study the controlled variable stiffness optimization on a ply-by-ply basis is used to optimize buckling performance. In the following section the parameterization followed by the numerical approach is described.

3 Methods

in this study two methods are used for the fibre steering optimization and for the following fibre path design. These two methods are presented in this section.

3.1 Parameterization and design space discretization

For the fibre steering design a ply-by-ply design space is used that can be seen as a compromise between a limited number of optimization variables and a large design space. The basis for the analysis is a finite element model where the fibre orientation per ply can be varied in each element. For the ETF structure the discrete element parameters in Abaqus are used. These per-element in-plane fibre orientations are controlled by a very limited number of control points which are interpolated using a spline definition from which a spline surface is constructed, see equation 1 and [12].

$$q(t) = 0.5 \cdot (2P_1 + (-P_0 + P_2) \cdot t + (2P_0 - 5P_1 + 4P_2 - P_3) \cdot t^2 + (-P_0 + 3P_1 - 3P_2 + P_3) \cdot t^3) \quad (1)$$

In which q is the interpolated value, t the normalized scalar along the spline and P_0 to P_3 the four control-points. In the ply-by-ply variable stiffness design the control points are mapped using a spline surface-like approach, see Figure 3.

Figure 3: (left) Example of local ply orientations (short lines) on a flat plate constructed by control points (dots) and interpolated by spline curves and spline surface (right) ETF full scale geometry with control point field distribution using an axisymmetric approach. The numerical element vector field will be interpolated per steered layer from these control point locations

With this approach a flexible mapping is achieved that can also be used for local thickness variations and for flat or curved topologies such as the ETF. For the ETF design an axisymmetric design for which 3 control points per layer are used in combination with symmetric laminates and balanced steered layer pairs. In total 6 to 9 control points for the design are used.

3.2 Optimization problem formulation

For the considered design optimization problem the objective is to find the highest ETF stiffness within the design space, see Figure 4. This design space is governed by the aforementioned orientation mapping but also by constraints. The optimization problem is formulated as:

$$\begin{aligned} \max_{d} \quad & J(d) \\ s.t. \quad & g(d) \leq 0, \\ & d \in [d_{min}, d_{max}] \end{aligned} \qquad (3)$$

Where J is the scalar design objective, g is a set of constraints and d is the set of design variables. The constraints g in this formulation are the design limits in terms of fibre orientations of the control points.

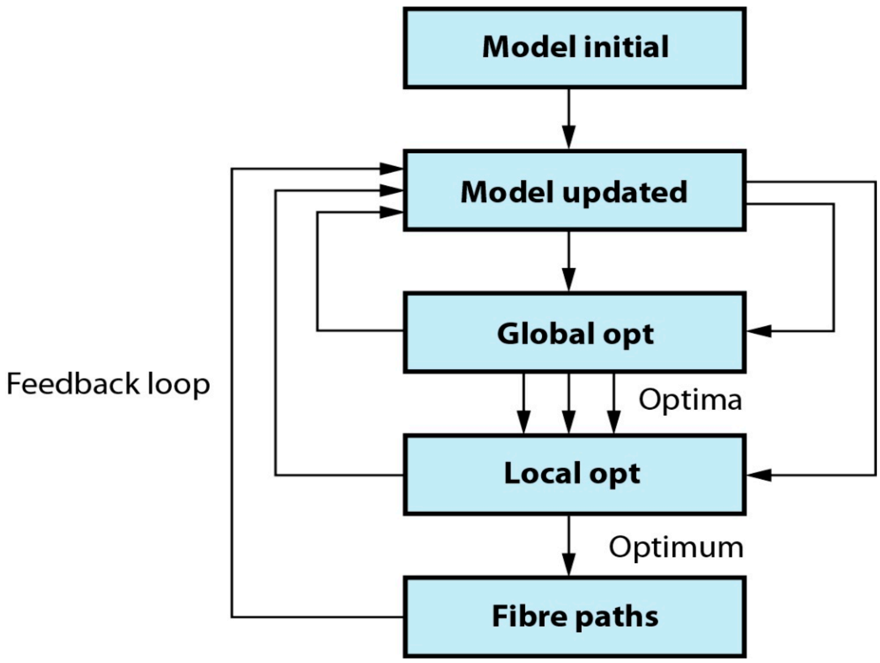

Figure 4: Overview of the optimization and feedback loop.
From the global optimization a selection of optima is chosen for the local optimizer.
The optimum is analysed with fibre paths and feedback for model update

In earlier research it was found that the optimization problem is complex and hard to capture with a surrogate model that would reduce the computational cost. The design objective field is highly nonlinear. Therefore the proposed approach for finding the optimum design efficiently is an initial global search algorithm for finding interesting design 'areas'. First a design space exploration is performed, followed by unconstrained gradient-based optimisation Python Scipy Fmin, OpenOpt NLP/NSP starting from the best result of the design space exploration. If the optimised stiffness exceeds the requirements for stiffness, the number of plies can be reduced to reduce the mass and the optimisation process can be performed again.

Design limits included in the optimization are the lower and upper bounds of the design variables to avoid undesired designs. Furthermore, manufacturing constraints for minimal radius of fibre curvature, which are related to the operational limitations of the advanced fibre placement machine, are accounted for. The optimisation was performed partly manually for the number of stiffeners, stiffener heights, and number of layers.

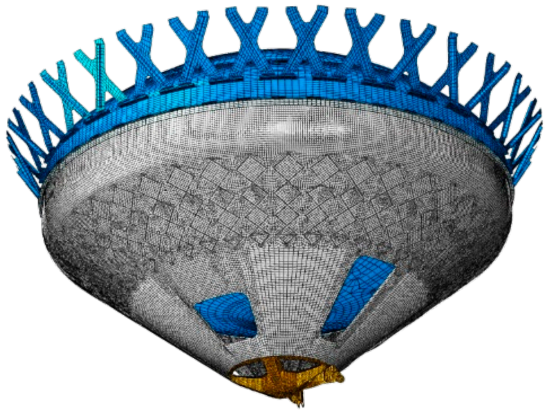

Figure 5: Engine thrust frame model/mesh with adjacent structures (adjacent tank structure in blue, engine frame/cone cap in orange). At the orange engine frame the thrust load and actuator loads are applied. The CFRP design consists of three different regions (green, white, grey) where the fibre steering is applied

A finite element model was used for the evaluation of the designs, see Figure 5. This numerical model including thermal loading (cryogenic at the interface with oxygen tank skirt) in the first timestep followed by the external engine thrust load in the second timestep. A reduced set of 9 loadcases are applied in the model, consisting of thrust loads, actuator loads and inertia loads. The fibre/resin system consisted of HexTow® IM7 carbon fibres in combination with the Cytec Cycom 5320-1 resin. This combination was selected as the material to be used for the design because of its favourable properties at cryogenic temperatures.

During the optimisation loop the balance between skin thickness, number of stiffeners and stiffener height was improved by performing finite element analysis to verify whether the design iterations met the requirements for stiffness, strength and structural stability. For the skin the fibre path of a predefined number of layers was optimised. Manufacturing constraints related to the automated fibre placement manufacturing were checked for the optimised fibre paths.

3.3 Fibre steering design - PathFinder

PathFinder is a Matlab [13] based in-house tool to construct fibre paths from local orientations as defined in the elements of a FE model ensuring manufacturability. From the midpoints of the elements and the vector field of the directions, the paths can be constructed as flowlines. In the original PathFinder, a 2D tool, the results from this are adapted in order to include manufacturability. Several aspects are addressed such as the tow width and the minimum bending radius as well as the selection of regions where the tows are similar. After this the manufacturability of the fibre steering design is evaluated using further analysis by checking the effect of adaptations. For manufacturability the new local direction are exacted and can be reused in FEM for the feedback loop, see Figure 4.
For the ETF design the tool is extended from 2D to 3D, to specific 3D objects that can be seen as (part of) an axial symmetric body. The fibre angles are translated into directions in the local tangent plane. The in-plane or geodesic curvature can be computed locally [14], where some smooth interpolation has been used. The manufacturability is taken into account in several ways. In order to use PathFinder, 1/3 of cone in circumferential direction has been projected in 2D together with the local direction vectors. First fibre paths are derived from the local orientations and smoothed such that a minimum bending constraint is fulfilled. One of them is picked and this curve is then rotated N times over $(360/N)^{o}$. The intermediate areas are then filled by orthogonal translations of the fibres. As is illustrated in

Figure 7. While the selection in this case was done manually, the interactive step can be omitted in a future automated process.
The tool finally produces .iges files that can be used directly in the manufacturing process.

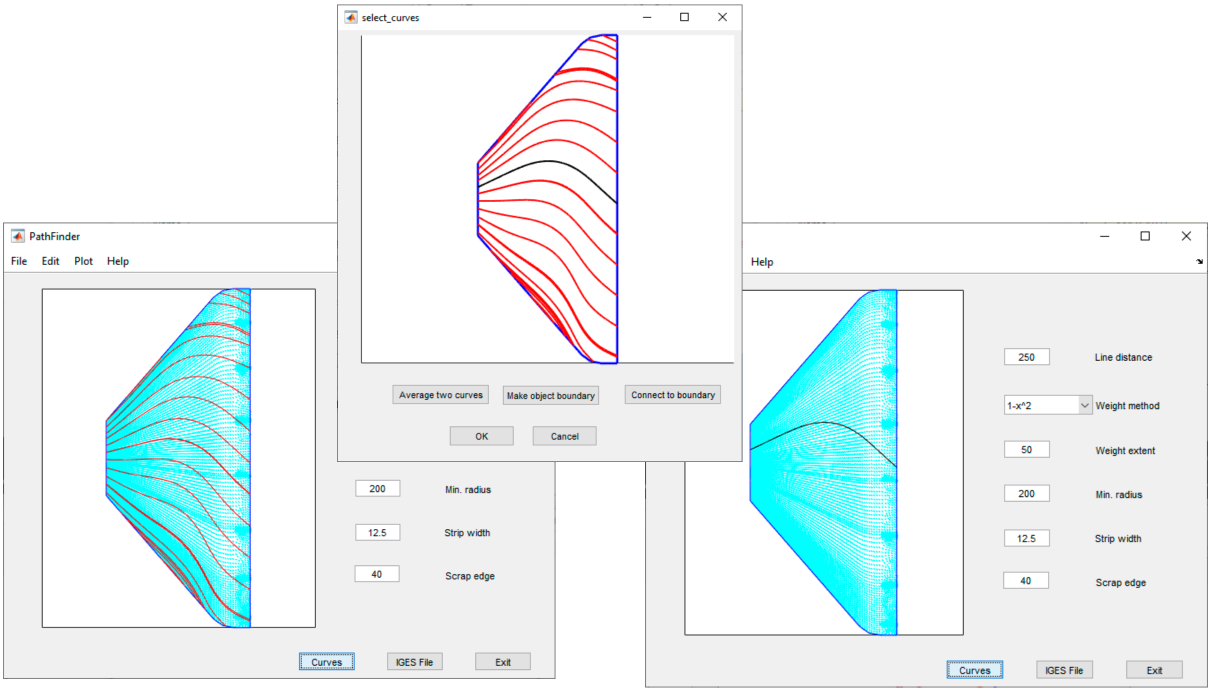

Figure 6: Illustration of use of fibre steering tool PathFinder

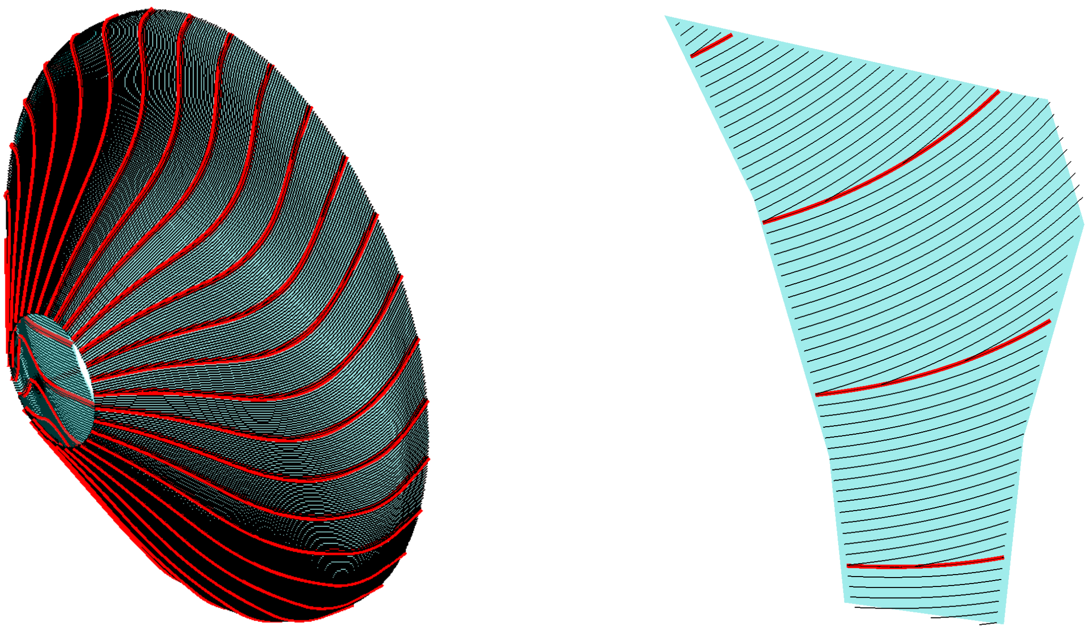

Figure 7: Example of placed fibre centrelines (left), and a detail of it (right). In the detail plot it can be seen that the red curve is translated (down) until the next red curve

In the next section the results of the fibre steering element level optimization and follow up fibre paths using PathFinder is presented.

4 Results

4.1 Fibre steering vector design

The optimization of the ETF is performed as described in the previous section. A Latin Hypercube Sampling (LHS) was performed to understand the global variation and changes in number of stiffeners and laminate thickness, see Figure 8. The objective is to optimize the stiffness in axial and transverse direction. From the LHS the optimal sets were extracted and further optimized using a local approach.

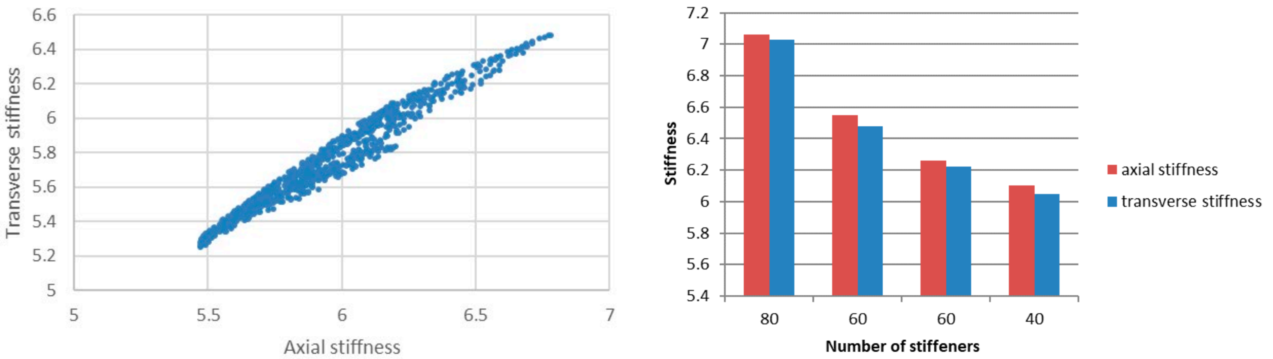

Figure 8: Output of variation of control points and resulting stiffness outputs in axial and transverse direction. As can be observed there is a strong relation between the two parameters

The LHS and stiffener variation investigation showed the sensitivities on the global level. The number of stiffeners has the highest sensitivity followed by the influence of the fibre steering. This was followed by the local optimization using a combined manual approach in changing the overall geometry and layup thickness. The variation of the design iterations are shown in Figure 9. A strong correlation between lower weight and lower stiffness which is compensated in the final design by the fibre steering laminate can be observed.

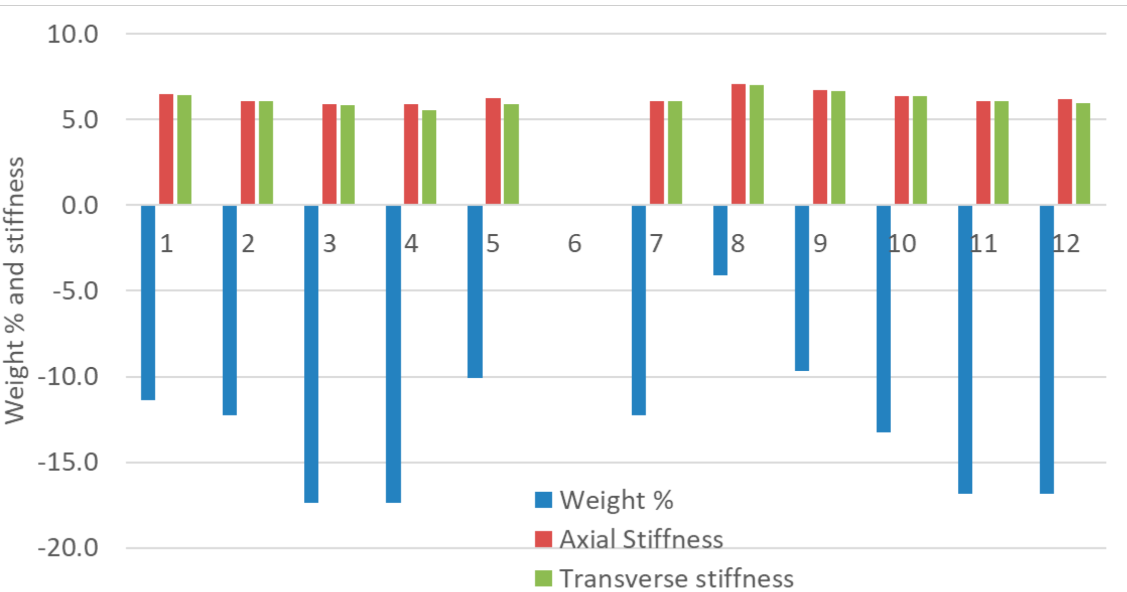

Figure 9: Variation of design iterations where the lay-up was changed

The resulting fibre orientations, shown in Figure 10, highlight the optimised stiffness of the engine frame. At the lower side the fibres run in axial or 0° direction while in the transition region from conical to cylindrical shape the direction changes to the hoop (90°) direction. In the cylindrical part the fibre direction tends to a 45° direction. In the laminate definition a layer with the optimised fibre path of Figure 10 is always accompanied by a layer with mirrored orientation in order to keep the laminate balanced. About 30% of the plies in the skin laminate have variable tow orientations. An increase of the number of steered plies would lead to a more orientated laminate which decreases the robustness of the design.

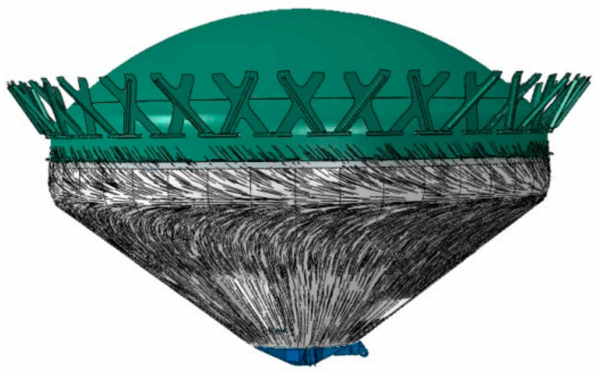
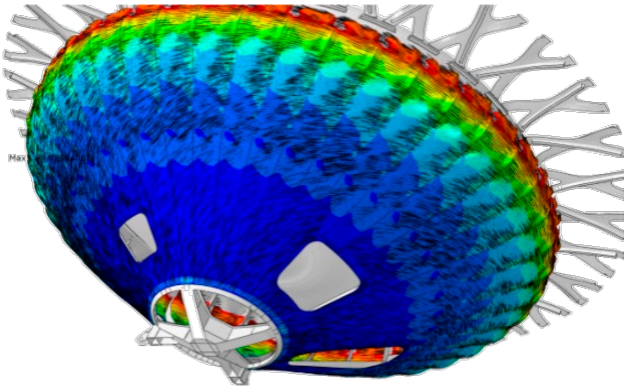

Figure 10: Optimal fibre orientation variation over the skirt for maximized stiffness (positively steered plies). On the right the temperature field and fibre orientations in 3D

The fibre steering design is the result of the optimization on global and local level and shows a clear benefit. An explanation for the resulting design can often be challenging because the optimizer can calculate interactions not always possible to comprehend. In this ETF design it is believed the axial fibre direction in the lower part is optimal because of the conical shape and strong axial dominating thrust load. Moving towards the transition area of the conical shape to the cylindrical section the fibre orientation strongly change to circumferential. It is believed this is caused in order to prevent the transition zone deforming outward under thrust and actuator load. This outward deformation will strongly reduce the stiffness. By placing the fibres in circumferential direction in the transition zone radial stiffness is increased.
The design was further improved by using so-called grid stiffening by smart overlapping [4] of the layers during fibre placement to increase the bending stiffness of the laminate which increases the structural stability and will especially be beneficial if equipment is to be mounted on the engine frame. This is outside the scope of this paper. The grid stiffening was tested in a coupon testing program to determine knockdown factors on compression strength transverse to the integrated stiffener and to evaluate the impact of the stiffness. An example of the displacements under load is shown in Figure 11

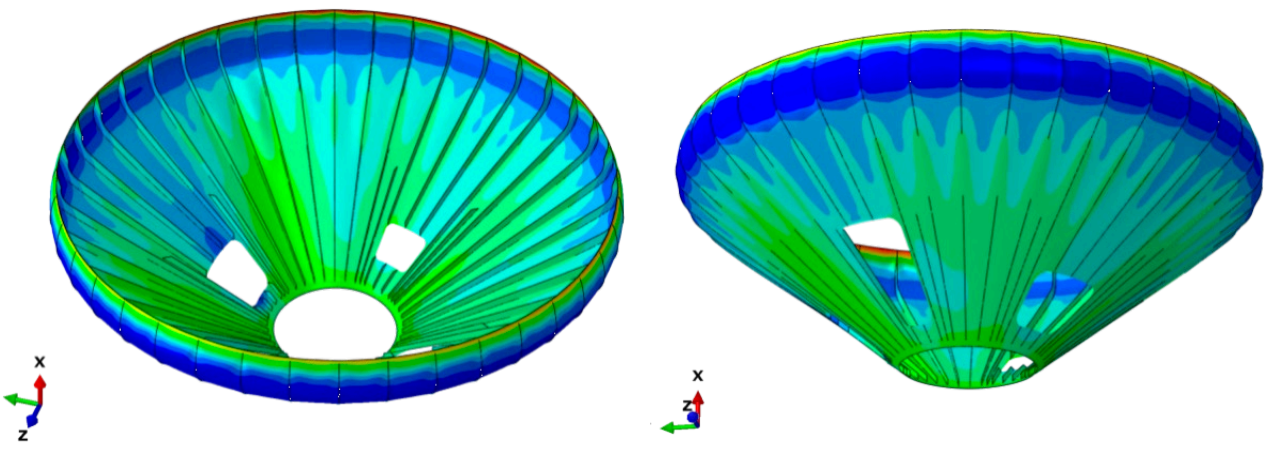

Figure 11: FEM calculation result with Temperature change and Axial load applied

The different design activities of the optimisation process led to a mass reduction of 15% compared to the initial composite design. With this successful result the fibre steering path was further detailed.

4.2 Fibre steering design

The large change in direction in the transition region leads to bending radii that are not manufacturable. The maximum angle in the vector field is therefore limited to the angle at the upper rim. After that a curve is extracted with PathFinder and the process of section 3.3 is applied. Due to the translation of the fixed fibre shape in a region as shown in Figure 7, some extra deviations form in the local vector field at certain positions. The indicative difference between the input orientations, already limited from the optimized and the computed orientations are depicted in Figure 12.

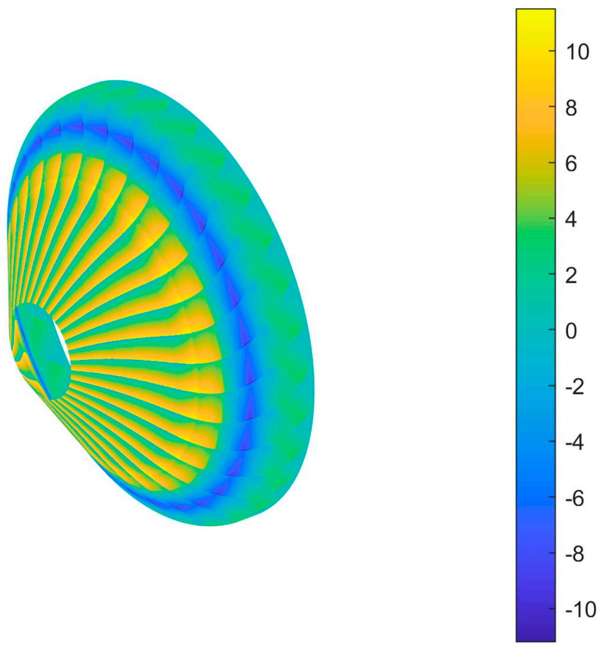

Figure 12: Indicative difference between the local angle in degrees of the computed fibre and the input orientation field. The repeated (yellow) pattern is due to the translation of the fixed fibre shape in a region as shown in Figure 7

4.3 Manufacturing and testing

The ETF as presented was used as the concept design from which the demonstrator design was derived. The demonstrator design uses a 1:3 scale and uses an updated fibre steering design, see Figure 13.

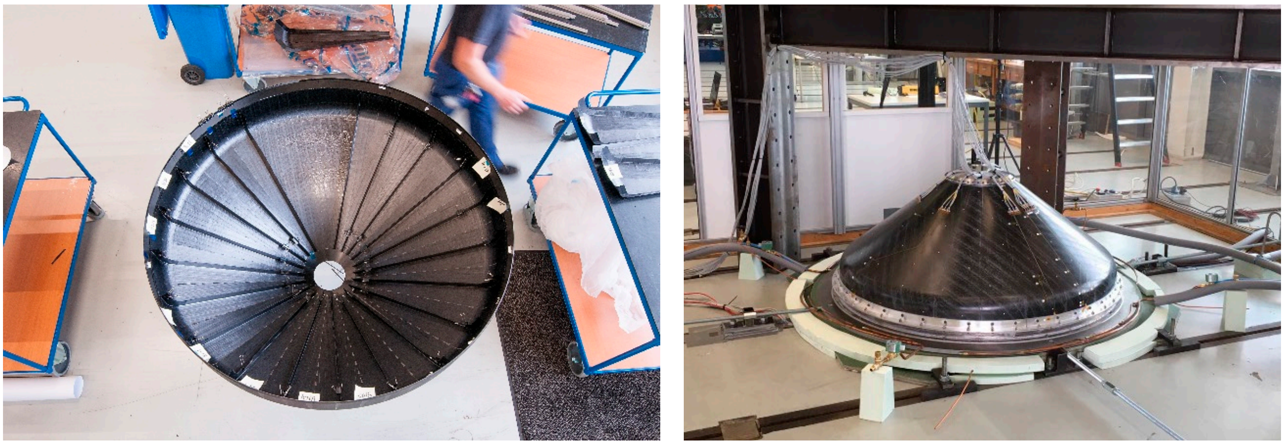

Figure 13: ETF demonstrator manufacturing with fibre steered skin and testing on the right

Feedback from the as-manufactured fibre paths and model updates for the test predictions were done by ADSN. The manufacturing and testing was successful but is outside the scope of this paper. For more information in the results the reader is referred to work by Poort *et al* [2].

5 Conclusions

In the presented research the aim is to lower the weight of the composite launcher Engine Thrust Frame (ETF) structure using different innovative design techniques such as laminate fibre steering making use of the AFP manufacturing process. Also, the reduction of the number of conventional stiffeners is an important factor. By doing this, the manufacturing process is simplified and becomes cheaper.

The full scale ETF was geometrically optimized for weight (reduction of conventional stiffeners) and successfully optimized in terms of composite ply orientations, for which active fibre steering method was used, also known as variable stiffness laminates method. A combined automatic and manual design optimization approach using the ply-by-ply control point approach was used for the laminate and geometrical design to achieve lowest weight of the cone. Both methods can be treated uncoupled; so the contribution from fibre steering optimization (stiffness performance optimization) comes on top of the sizing optimization.

With the optimized design including 40 stiffeners and fibre steering the design requirements were met. The weight is reduced 15% from the conventional CFRP design to the optimized design including manufacturing constraints. Due to the reduced number of stiffeners compared to the reference the manufacturing cost will be significantly lower. Weight saving results in less material cost and related processing time, leading to higher cost saving. The demonstrator derived from this design on 1/3 scale was successfully manufactured and tested and showed the benefits of CFRP fibre steering design for ETF.

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