STRUCTURAL OPTIMIZATION TO DERIVE FEASIBLE AND MANUFACTURABLE TAILORED FIBER PLACEMENT (TFP) DESIGNS

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ABSTRACT

Production technologies for Fiber Reinforced Plastics (FRP) have been extensively researched with the goal of achieving light weighting targets and reducing process costs through efficient material utilization. Tailored Fiber Placement (TFP) is one such technology that offers unique advantages. TFP allows for the precise placement of fibers along optimal load paths, providing essential structural reinforcement while reducing waste and material costs. By using fiber path optimization methods and TFP technology to optimize the relationship between load case and fiber orientation, the performance of endless fiber composite materials can be significantly enhanced, achieving unparalleled results. In this paper, we present a novel approach to this design optimization problem using a hybrid and powerful automatic optimization engine (Isight and Abaqus). The design space is represented by two variables: Finite Element (FE) shell thicknesses, which indirectly represent the amount of fiber rovings, and fiber orientations within the design domain. We demonstrate this approach using a simple cantilever beam FE model. When carefully implemented with meaningful manufacturing constraints, our approach could be used to exploit the advantages of TFP and other manufacturing methods to generate optimal high-performance structures.

1 INTRODUCTION

Fiber reinforced composites are gaining popularity across various industries due to their exceptional combination of strength, stiffness, and lightweight. As a result, the development and production of these composites has become a crucial area of research and innovation. Combining current and traditional manufacturing methods to take advantage of design freedom can be highly beneficial for light weighting. Tailored Fiber Placement (TFP) is one such technology that offers unique advantages. This section provides a clear and concise overview of TFP technology and motivates our research in this area towards the end.

1.1 Tailored Fiber Placement (TFP)

TFP remains a strong competitor to technologies such as endless fiber reinforced 3D printing or Automated Fiber Placement (AFP) due to its ability to produce high-quality preforms with highly curvilinear placed reinforcing fibers at a high level of productivity [3]. This technology was developed in response to an industry inquiry about stress-adapted fiber-reinforced plastic (FRP) parts with a curvilinear pattern. TFP technology provides complete control over the placement and direction of fibers in a composite preform. This results in the creation of highly engineered composite structures that fully utilize the anisotropic properties of fiber reinforcement. As noted in [8], composite parts made of TFP could provide a significant boost in load bearing capacity. It has also found applications in the aircraft industry, such as airplane window frames. Figure 1, below illustrates the operating principle of TFP process.

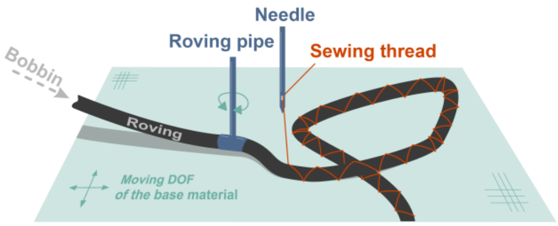

Figure 1: TFP operating principle (Image adapted from [3])

TFP involves stitching fiber rovings onto a base material to produce composite dry preforms that can later be used as reinforcements in critical locations. The process uses specialized embroidery machinery to deposit and stitch fiber roving material onto the base material. The preform is produced by continuously placing a single roving, which is guided by a roving pipe in front of the stitching needle. The roving pipe and frame move in sync to perform a zigzag stitch relative to the needle position.

TFP technology has several benefits compared to traditional laminate technologies. One of these benefits is the reduction of waste material by precisely placing material only where it is required in the final preform. Other benefits of TFP technology include the ability to create hybrid carbon-glass fiber composites, adjust fiber alignment, customize localized thickness and production automation. One of the key advantages of TFP is, its machine versatility, which allows for rapid adaptation to produce completely new parts without the need for retooling. This results in more efficient use of materials and greater flexibility in production capabilities.

This study focuses on developing practical and producible preforms for use as structural reinforcements using TFP technology. To ensure that design recommendations from simulations are manufacturable, manufacturing constraints must be considered within the optimization framework. This paper introduces a novel approach to simultaneous fiber path and thickness optimization, with the ultimate goal of creating an optimization framework that incorporates pragmatic manufacturing constraints, minimizes post-processing, and quickly derives optimal design recommendations within the feasible design space. In this approach, fiber rovings are indirectly represented by the thickness of 2D finite element shell elements, and section-averaged fiber orientation allows for the calculation of the fiber placement path after the optimization process is complete. These problem statements motivate our current and future research, and we aim to answer these challenging questions using available simulation tools.

2 COMPOSITE DESIGN OPTIMIZATION

Composite materials offer excellent mechanical properties, but to fully utilize this advantage, it is necessary to optimize the shape, size, and fiber orientation over the structure. The goal of composite design optimization is to achieve specific performance objectives for the desired component by selecting the optimal set of design variables. In this section, we will review relevant research in this field, categorize design optimization problems based on various factors, and discuss the primary motivation behind our research work.

The mechanical properties of composite materials are heavily influenced by design factors such as fiber orientation, stacking sequence, and layer thickness. As a result, optimizing these parameters to meet specific performance requirements is a crucial part of the composite design process. This has been an active area of research for several decades, with design variables including ply orientations, fiber volume fraction, number of layers, stacking sequence, fiber and matrix materials, and layer thickness. Common objective functions in optimization studies include buckling load, fundamental frequency, weight, load carrying capacity, deflection. The field of composite design optimization has seen significant contributions from many researchers, as documented in [1], [4], and [6].

Composite design optimization problems can be categorized in many ways, taking into account factors such as the type of structure, objective functions, design variables, constraints, and algorithms used in the optimization process, as described in [4]. However, [1] provides a simple classification for laminated composite structures based on design variables, and are constant stiffness, variable stiffness, and topology optimization design problems.

2.1 Constant stiffness design

In constant stiffness design, the goal is to find a combination of unidirectional-fiber layers with uniform thicknesses, where design variables remain constant throughout the ply domain. This results in constant stiffness properties. Design variables, which define the arrangement of constituent materials in a laminated composite material, include the number of layers, thickness of each layer, fiber orientation within each layer, and stacking sequence of layers. By optimizing these parameters, designers can create composite materials with specific mechanical properties and performance characteristics. The objective is to find the best set of design variables for desirable structural performance.

2.2 Variable stiffness design

In variable stiffness design, fibers can follow curvilinear paths within the laminate, leading to improved structural performance. Stiffness could be altered through fiber steering or ply drops, resulting in superior performance compared to constant stiffness design [2], [5]. However, variable stiffness design has attracted fewer researchers due to higher design and manufacturing costs. The higher design cost is due to the large number of design variables required to define variable orientations and thicknesses, as well as additional constraints for maintaining continuity in the structure, which requires more computational resources than constant stiffness design [5]. After reviewing over 200 research papers on composite design optimization from 2000 to 2017, Ghiasi et al. [5] ranked optimality criterion methods and topology optimization with a local update rule as the best candidates for variable stiffness designs. This paper focuses on variable stiffness - design optimization problems, as they are well suited for TFP.

2.3 Topology design

Topology optimization (TO) seeks to determine the optimal material distribution within a given domain for given loads and boundary conditions in order to minimize or maximize the objective function. In recent years, material distribution and fiber orientations in composites have been optimized simultaneously [1]. In the author’s previous works, topology optimization was utilized to optimize the layout of a predefined quasi-isotropic composite layup [9]. Additionally, methods such as 3D topology optimization using Bidirectional Evolutionary Structural Optimization were also investigated.

3 METHODOLOGY

In the author’s previous works, manufacturing constraints were not modelled, as stated at the end of section 2.3. Drawing on recommendations from the literature, as mentioned in section 2.2, we propose a new modelling approach that addresses the drawbacks identified in our previous research. To provide a proof of concept for our novel approach, we begin the optimization process with a well-known problem in mechanical engineering: a cantilever beam subjected to edge loading. Figures 2 (a) and (b), depicts the finite element model, along with its loading and boundary conditions.

The cantilever beam depicted in Figure 2 is divided into a grid of 12 sections, each with a predefined thickness and a section-averaged fiber orientation. The beam is discretized using a 4-node, general-purpose 2D shell finite element (S4) in ABAQUS with three integration points through the thickness. The material behaviour of a linear elastic and orthotropic material is characterized by nine independent engineering constants: the three moduli (E_1, E_2, E_3), Poisson’s ratios (Nu_{12}, Nu_{13}, Nu_{23}), and the shear moduli (G_{12}, G_{13}, G_{23}). These constants are specific to unidirectional carbon fibers and are shown in Table 1. Each element has an associated material orientation, referred to as fiber orientation.

Within the optimization process, each section represents two design variables: fiber orientation and shell thickness. In the context of TFP, shell thickness indirectly represents the number of the fiber rovings. Subsection 3.1 provides a detailed description of the optimization process and explains the significance of the problem being addressed. The right vertical edge of the FE model is subjected to a load of 100 N in negative Y-direction, while all degrees of freedom for nodes on the left extreme edge are arrested.

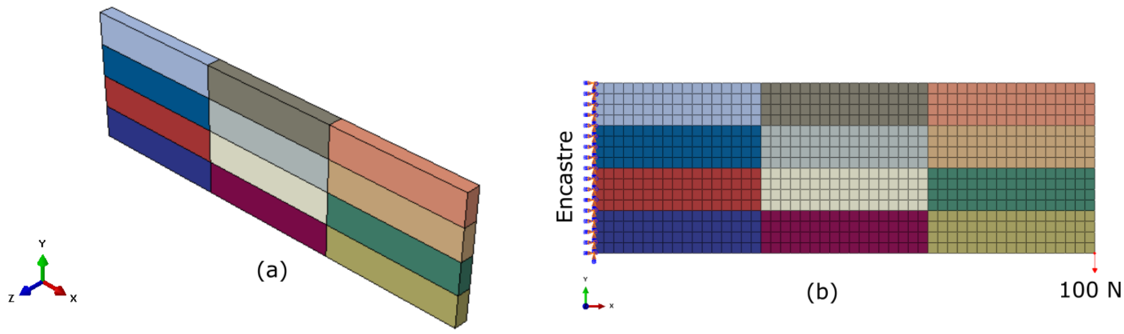

Figure 2. (a) Sectional representation of the chosen beam Geometry (full size: 75 mm × 25 mm × 5 mm), (b) FE domain discretization - 2D S4 shell element, with load and boundary condition

E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	Nu_{12}	Nu_{13}	Nu_{23}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
121000	8600	8600	0.27	0.27	0.4	4700	4700	3100

Table 1: CFRP Material properties

3.2 OPTIMIZATION

Often, the results of an optimization process are not directly applicable to manufacturing. As a result, additional post-processing and engineering judgment are necessary to develop a manufacturable design. However, when our proposed method is implemented with consideration for manufacturing constraints (which are not discussed in this paper), it can effectively utilize TFP or other fiber placement technologies to avoid impractical structures with discontinuous fiber orientations and produce high-performance structures. Considering manufacturing constraints is crucial in preventing impractical structural discontinuities.

In this research paper, we address a variable stiffness design optimization problem, as outlined in section 2.2. Our approach utilizes a discrete parameter optimization technique. Objective of the optimization is to minimize the magnitude of maximum displacement in the composite beam, with shell thickness and fiber orientations as design variables. Shell thickness is constrained to vary between the bounds of 0.5 - 4 mm, while the fiber angle design space ranges from -90° to +90°. The volume fraction constraint represents the final volume of the composite beam after optimization. Volume constraint is implemented as an equality constraint. The simulation process is automated using Isight, a process automation and design exploration software from Dassault Systèmes.

4 RESULTS AND DISCUSSION

In this section, we present and analyze the outcomes of our initial thickness optimization subject to a target volume constraint. Figures 3 and 4 illustrate the optimization process with a 45% volume constraint and show the evolution of the objective function graph over the course of the optimization.

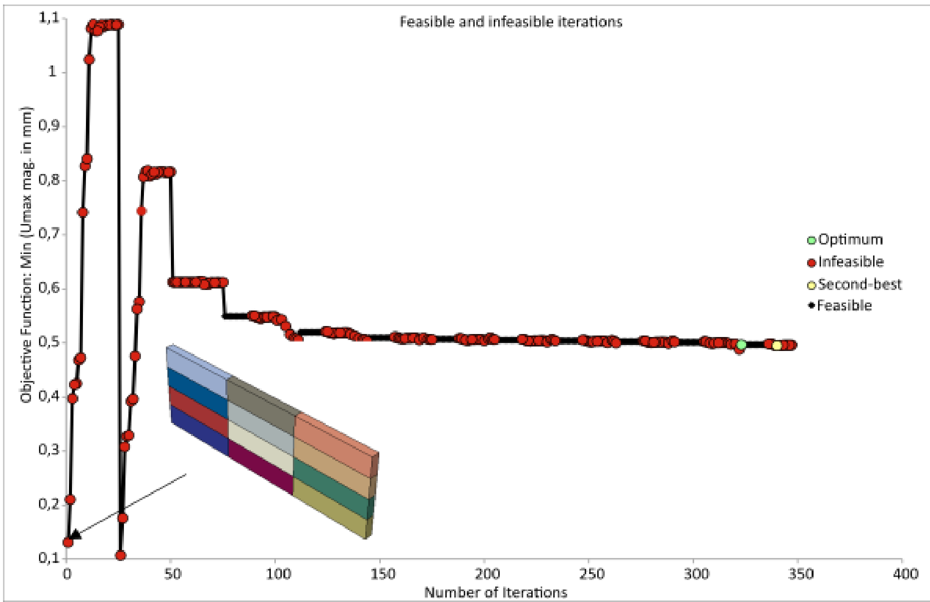

Figure 3: Convergence curve with feasible and infeasible iterations (45%)

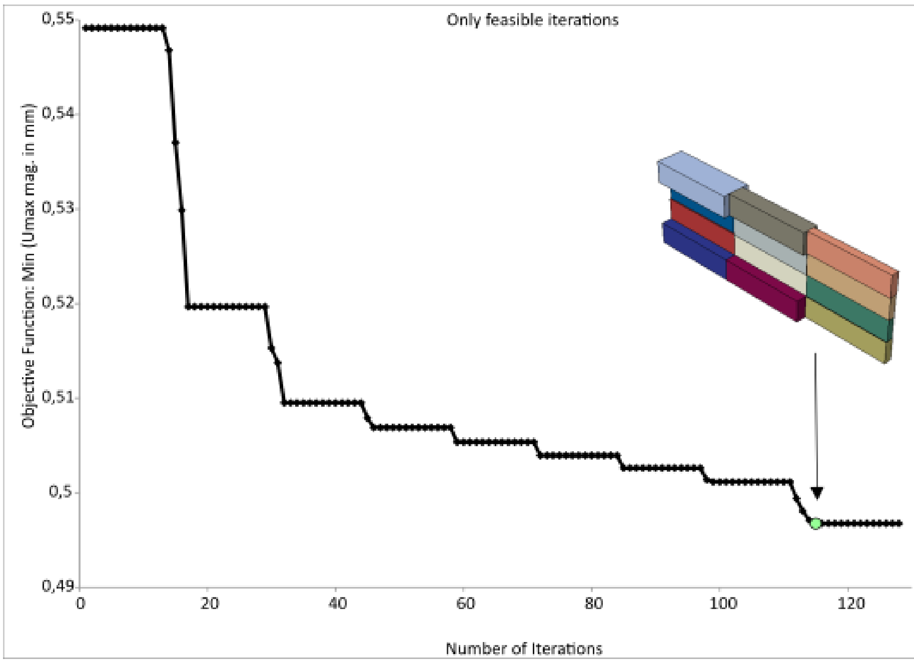

Figure 4: Convergence history in the feasible design space

In Figure 3, the convergence history is depicted with both feasible and infeasible design points. At iteration 1, the initial thickness configuration of the FE model is 1.25 mm, which is close to the lower bound of the thickness design variable. The volume fraction is 31.25%, falling below the target volume constraint of 45%. The fiber orientation is uniform and set to 0° in all sections.

Starting in the infeasible space (indicated by red points), it eventually reaches the feasible space (indicated by black points) by thickening sections where necessary. Figure 4. shows that the top and bottom sections are thickened while the middle row of sections remain unchanged and determines that sections closest to fixed nodes should have maximum thickness. Thus, the optimizer aims to achieve an I-section configuration, which is optimal for bending problems where the top and bottom sections are subjected to tension and compression, respectively.

Although the initial configuration had a low objective function value (before to the the start of optimization), it deteriorated during optimization. The reason for the difference could be that the optimal fiber orientation was identified to be 90° in all cross sections. This is incorrect for a cantilever beam with edge loading. To carry tensile and compressive loads, the top and bottom sections should have a 0° orientation, while the middle row of sections should be aligned in the direction of the load path. As a result, the worsening of the objective function might be linked to the optimal fiber orientation. This will be discussed in detail at the end of results section.

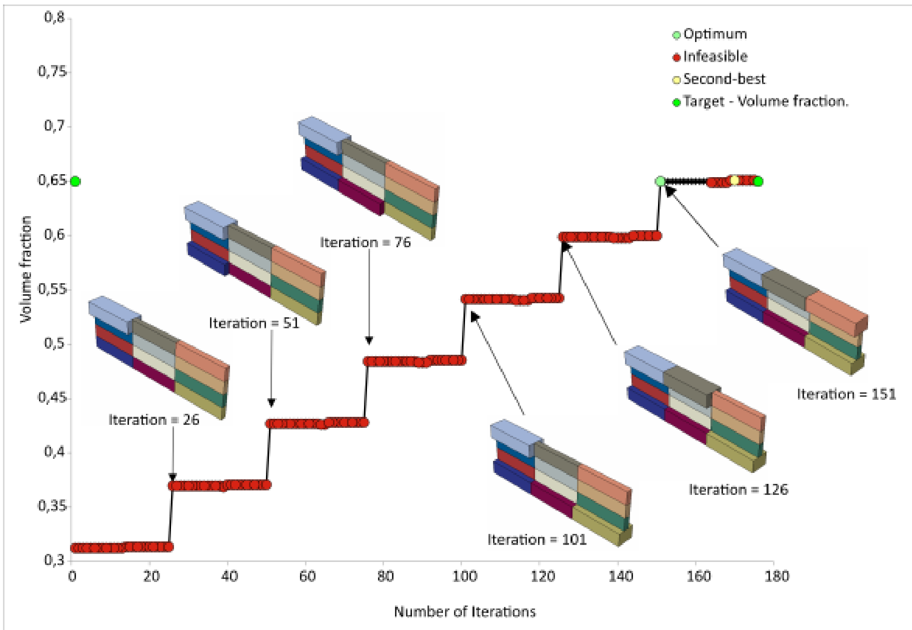

Figure 5: Optimization iteration history (65%) versus volume fraction

Figure 5 illustrates the sectional thickness additions at various iterations, starting with the most stressed sections (iterations 26 and 51) and gradually thickening the tensile and compressive cross-sections at the top and bottom respectively until the target volume fraction is reached. Another study was conducted to understand the impact of volume constraint on thickness optimization by varying the volume constraint from 25% to 85% in increments of 20%. The results showed that a perfect I-beam cross-section was identified as optimal in the feasible zone with a 65% target volume constraint.

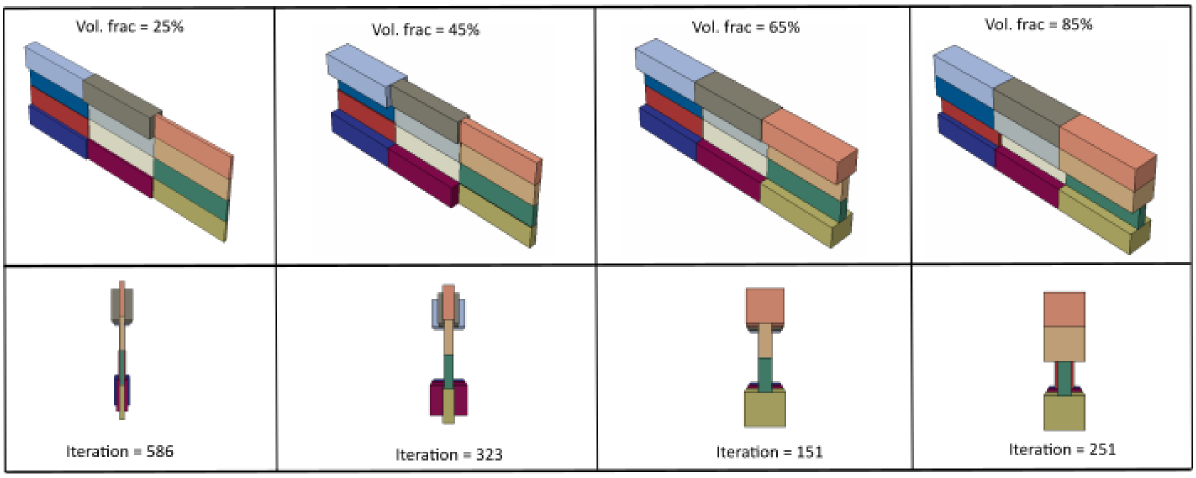

Figure 6: Effect of volume constraint on thickness distribution

Figure 6. depicts the optimum thickness configurations for different volume constraints in isometric (top) and side views (bottom). From Figure 6 and Table 2, it is clear that, with the reduction in volume fraction, the optimizer needs more iterations to find the optimum and that the highest time is consumed by the 25% variant. The optimization process was fully automated and parallel Abaqus simulations were carried out in each optimization loop. In all cases except one, convergence was achieved within 3-7 minutes. However, it should be noted that since the simulations are automated, there may be additional time overhead for license waiting. This can result in longer convergence times despite fewer iterations.

Volume	Iterations	Time (min.)	Optimized displacement (mm)
25 %	736	45	0.947
45 %	348	3	0.496
65 %	176	7	0.398
85 %	276	3	0.364

Table 2: Time to convergence and optimized displacement

As mentioned at the beginning of this section, we performed a sequential fiber angle optimization on the I-beam thickness optimized structure to see if a better fiber orientation could further minimize the objective function. As shown in Figure 7, a better fiber orientation was found with an improved objective function value of 0.0414 mm, compared to the displacement before optimization (0.13 mm) and at optimum (0.398 mm – refer Table 2). Figure 7 presents the final recommendation with optimal thickness and fiber orientation for the given load situation at 65% volume fraction.

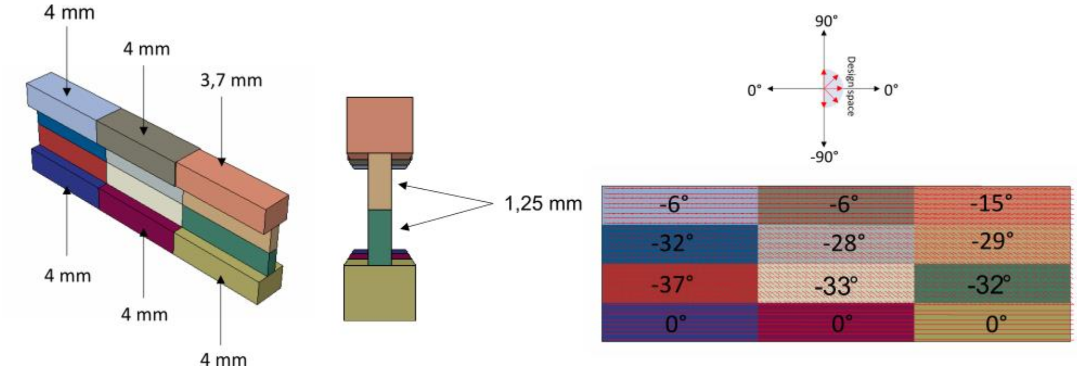

Figure 7: Summary of Optimized result

Figure 7 illustrates the final recommendations for thickness, with the top and bottom sections at their maximum value of 4mm and relatively thinner middle sections. The fiber orientation predictions for tension and compression at the top and bottom sections are quite accurate, with the bottom section at zero degrees and the top section near zero, slightly inclined towards the load. In the mid region, fiber angles are oriented in the direction of the load path. Although the results align reasonably well with existing literature [7], there is potential for improved fiber orientations. This approach shows great promise and the results presented lay the foundation for future developments. The following section will outline plans for conducting further research.

5. CONCLUSIONS AND OUTLOOK

A novel optimization strategy with volume constraints for variable stiffness design optimization problem has been successfully demonstrated using a simple academic problem. The proposed technique strikes a fair balance between the competing need for faster yet accurate optimization and extremely detailed analysis. Future research plans include modelling detailed manufacturing constraints, extending thickness and fiber steering constraints, and investigating how computational costs scale with finer meshes. The generality of the proposed approach and simultaneous optimization will also be explored. With its automated and highly parallelized efficient simulations, this technique offers a promising outlook for the future.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Xu, Y., Zhu, J., Wu, Z., Cao, Y., Zhao, Y., & Zhang, W. (2018). A review on the design of laminated composite structures: constant and variable stiffness design and topology optimization. Advanced Composites and Hybrid Materials, 1(3), 460-477.

[2] Irisarri, François-Xavier, Daniël MJ Peeters, and Mostafa M. Abdalla. "Optimisation of ply drop order in variable stiffness laminates." Composite Structures 152 (2016): 791-799.

[3] Spickenheuer, Axel, et al. "Tailored fiber placement in thermoplastic composites." Technologies for Lightweight Structures (TLS) 1.2 (2017).

[4] Nikbakt, S., Kamarian, S., & Shakeri, M. (2018). A review on optimization of composite structures Part I: Laminated composites. Composite Structures, 195, 158-185

[5] Ghiasi, Hossein, et al. "Optimum stacking sequence design of composite materials Part II: Variable stiffness design." Composite structures 93.1 (2010): 1-13.

[6] Mattheij, Paul, Konrad Gliesche, and Dirk Feltin. "Tailored fiber placement-mechanical properties and applications." Journal of Reinforced Plastics and Composites 17.9 (1998): 774-786.

[7] Jiang, Delin, Robert Hoglund, and Douglas E. Smith. "Continuous fiber angle topology optimization for polymer composite deposition additive manufacturing applications." Fibers 7.2 (2019): 14.

[8] Khaliulin, V. I., P. A. Khilov, and D. M. Toroptsova. "Prospects of applying the tailored fiber placement (TFP) technology for manufacture of composite aircraft parts." Russian Aeronautics (Iz VUZ) 58 (2015): 495-500.

[9] Nagaraj, V., Motsch-Eichmann, N., Hausmann, J. “Anisotropic topology optimization of carbon fibre reinforced composite materials engineered with novel manufacturing technologies.” ECCM20 - 20th European Conference on Composite Material, Lausanne, Switzerland, 26-30th June 2022.