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Influence of Reinforcement Initial Positions in Optimization on CRFP Plates

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Abstract: Carbon Fiber Reinforced-Placement (CRFP) has great prominence in high-tech projects. The progress of manufacturing processes made it possible to manufacture composites with curvilinear fibers that are independent of each other, so Variable Stiffness Composites (VSC) were developed. The Variable Angle Tow (VAT) is a class of reinforcement deposition techniques, mainly used in plates, which have a non-linear orientation and that can be different in each ply. The orientation of the reinforcements is one of the main variables for changing the mechanical properties, so the implementation of optimization in the fiber paths becomes a powerful tool in the development of better components. In this work, Linear Programming method is successfully applied to obtain optimal fiber orientation in such cases. Plates were optimized using Sequential Linear Programming. Altogether, four case studies were carried out, containing one boundary conditions and four different initial positioning of the reinforcements were evaluated. It is important to highlight that in all cases the objective function was to minimize compliance and the number of reinforcements was three. Thus, it was possible to observe that there is considerable variation in final compliance. This could be proven by the case studies, after optimization the orientations with the best and worst performance showed a difference in strain energy of 280%.

Keywords: Structural Optimization; Linear Programming; CRFP; VSC.

INTRODUCTION

One of the main demands in current mechanical projects is the reduction of structural weight, keeping the properties of the components within safe limits for the operation of the equipment. In this sense, the gradual replacement of metallic parts by composites has become a trend, especially in industries such as aerospace and automotive (Aragh et al., 2021). Among the main composites used in the design of structures is the CRFP (Carbon Fiber Reinforced-Placement), which are fundamentally carbon fiber reinforcements deposited in a polymer matrix. These materials, in addition to having low weight, stand out for their high stiffness and strength (Das, Sahu and Parhi, 2021). According to Konieczny and Labisz (2021), there are several constructive conditions that change the mechanical characteristics of fibrous polymers. However, fiber orientation is one of the most important aspects for defining these characteristics, becoming one of the main focuses of current projects. The suitable positioning of the filaments allows the anisotropic behavior of the CRFP to be taken advantage of. Therefore, the implementation of structural optimization methods to the reinforcements allows to obtain the best positions and orientations of the fibers, achieving better properties for the component (Nikbakt, Kamarian and Shakeri, 2018).

Due to the development of advanced manufacturing techniques, it was possible to build parts with curvilinear fibers. Because of this, VSC (Variable Stiffness Composites) could be built, which have different stiffness indices along the body (Brooks and Martins, 2018). Furthermore, through the use of methods known as VAT (Variable Angle Tow) pieces are designed with reinforcements of different orientations in each layer, in this way, the position of the filament is independent of the others. So, mechanical components with complex shapes started to be built, in a way that guarantees not only mechanical but also geometric specificities of each project (Kesarwani, 2017).

Fiber optimization can be performed by two main groups of methods: angle discretization, which consists in the individual optimization of the orientation of each finite element of the structure, or the parameterization of the curve, which represents the reinforcement path. Among them, the parameterization of the curve has the advantage of being able to achieve optimized orientations in a restricted number of design variables (Nikbakt, Kamarian and Shakeri, 2018). In initial studies, Gürdal and Olmedo (1993) used linear functions to solve these problems, which consisted of maximizing the strength of plates. In a more recent context, Hou et al. (2021) applied cubic splines to avoid stress concentration in materials reinforced by curvilinear filaments. In turn, Wu, Raju and Waver (2015) implemented B-Splines to represent the fibers in plates with variable stiffness. According to the results obtained, the application of B-Spline is advantageous in relation to other polynomial functions because it reduces the probability of obtaining the non-convex problem. In addition, it maximizes properties while developing smooth, continuous curves.

Structural optimization has several classical methods that can be used to obtain the best positions of the reinforcements. One of these techniques is linear programming, which uses both design variables and linear objective functions. From this, it is possible to implement sequential linear programming, which approximates the equations of linearity through Taylor Series (Arora, 2016). In order to obtain the first derivative, which is fundamental for implementing the Taylor Series, the Finite Difference Method can be used, in which an approximation of this value is reached after the application of an infinitesimal perturbation on the design variable. Also, it is worth mentioning that, to reduce the computational cost, limits are implemented with values that are not fixed, and vary at each iteration, called Moving Limits. They are reduced or expanded according to the history of last three results achieved in the cycles of the optimization process (Nocedal and Wright, 2006).

Several variables used in the process influence the final compliance value of the components optimized by this method. As the dimension between the lower and upper limits of the Moving Limits is variable, not only this initial value but also their opening and closing percentage influence the process. Thus, it is possible to state based on the literature that high initial values for the limits obtain a shorter conversion time, reducing the computational cost. On the other hand, when they are implemented with stricter limits, there is a tendency to achieve results closer to the global optimum, but with longer processing time (Arora, 2016). It is worth mentioning that one of the most influential variables in the result is the initial positioning of the fibers. This boundary condition, still little explored in academic works, when not well defined, can even make the optimization of the structure unfeasible, inducing the algorithm to obtain worse results than the initial non-optimized condition. Therefore, the present work aims to observe the influence of the initial orientation of reinforcements in reducing the compliance of plates subjected to tensile loads.

METHODOLOGY

The work consists of optimizing the paths of three carbon fiber reinforcements applied to plates made of epoxy resin. Table 1 presents the properties of the materials used in the simulations (Sonden, Hinton and Kaddour, 1998).

Table 1 – Properties of the materials used in the matrix and reinforcement of the

Properties	Carbon Fiber	Epoxy Resin
Longitudinal Young's Modulus (E_1)	230 GPa	4 GPa
Transverse Young's Modulus (E_2, E_3)	15 GPa	4 GPa
Longitudinal Shear Modulus (G_{12})	15 GPa	1,481 GPa
Transverse Shear Modulus (G_{23}, G_{32})	7 GPa	1,481 GPa
Longitudinal Poisson's Ratio (v_{12})	0,2	0,35
Transverse Poisson's Ratio (v_{23}, v_{32})	0,07	0,35

The optimization process takes place through the implementation of Linear Sequential Programming and their objective is to reduce the compliance of the structure. Obtaining the optimum is performed by the continuous interaction between Ansys APDL and MATLAB software. Each of the reinforcements is represented by a B-Spline, which has six design variables (positions and angles of inclination of the beginning and end of the curve). In the foreground, an infinitesimal perturbation is applied to the design variables and, in Ansys, the change in stiffness is calculated by the Finite Element Method. Then, the values are exported to MATLAB, where their first derivative is calculated, using Finite Differences. So, by Linear Programming, the optimal variables are obtained. Then, the new variables are exported to Ansys and used to calculate the strain energy of the structure. Also, the new positions are used as a basis for starting the calculation of the later iteration. This process is repeated until there is no more significant change in the design variables (change less than 10-5) or 1000 cycles are completed.

The structures studied are four identical plates, which have a thickness of 10mm, and their height and length are equal to 100mm. The structures are supported at the vertices of the located vertical edge, at the point x = 0 and y = 0 and at the point x = 0 and y = 100. These restrictions allow only rotation, preventing any type of translation at these points. The plate used in all the cases studied, shown in Fig. 1, is subjected to a point load of 1 kN in the positive direction of the x axis, applied to the point with coordinates x = 100 and y = 100.

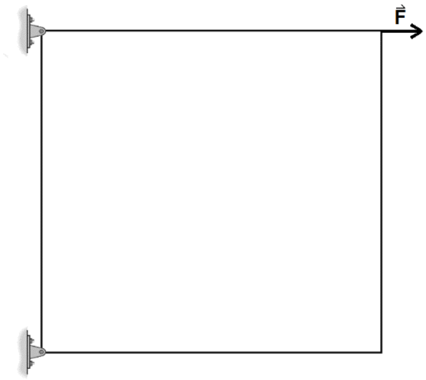

Figure 1 – Boundary conditions of the plates applied in the work

The plate configurations were reinforced by three carbon fiber filaments, with a cross-sectional area equal to 4 mm². For each of the structures studied, there was a difference in the initial positioning of the reinforcements, configuring four different cases. In addition to presenting equidistance and parallelism to each other, the initial reinforcements were straight. As can be seen in Fig. 2, we have reinforcements with inclinations equal to 0°, 90°, 45° and -45° in relation to the x axis.

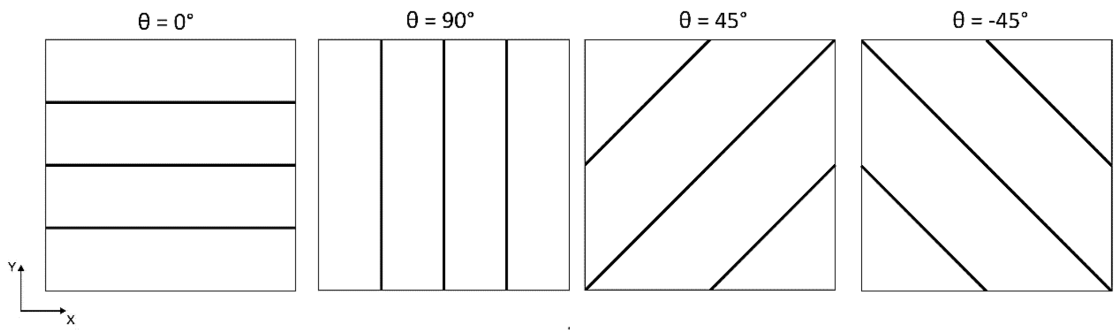

Figure 2 – Initial orientation of the four cases studied

Then, four case studies are configured. After performing the fiber optimization, the compliance of each of their structures is calculated - adding the strain energy of each of the finite elements - and the results are compared and discussed.

RESULTS AND DISCUSSION

Figure 3 shows the final positioning of the fibers in each of the cases discussed, after the application of the optimization process. As can be seen, the final morphology of the reinforcements is quite different, presenting completely different positioning from each other and from their respective initial configurations.

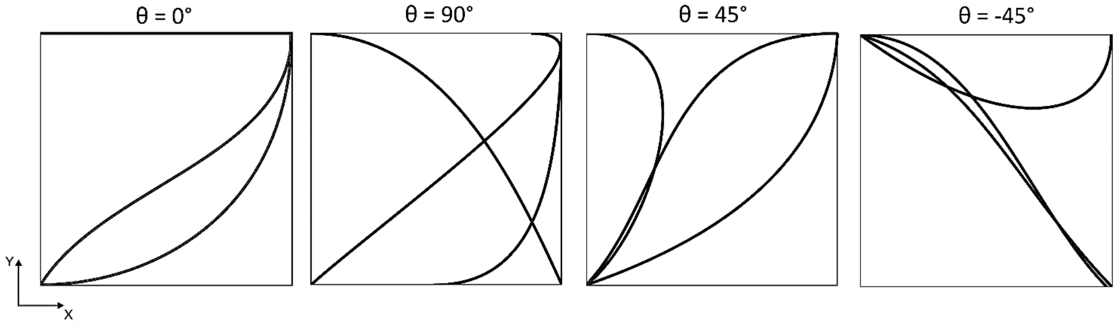

Figure 3 – Final orientation of the four cases studied

In most cases, the reinforcements, which could assume any position and angle along the area of the plate, sought the initial or final positioning at the support points or at the point of application of the load. In only one situation, θ = 0°, there was no change in the tangent angle of the curve, keeping it straight and translating to the position where it was aligned to the force and supported by the constraint.

In order to discuss the numerical results of the study, Fig. 4 shows the compliances obtained from the initial positioning of the structures and the value obtained after the optimization.

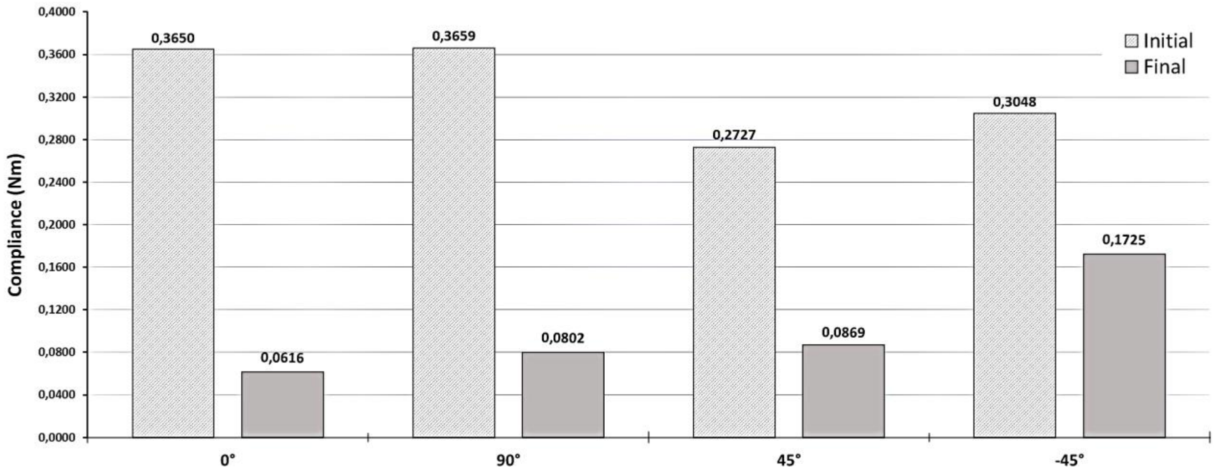

Figure 4 – Initial and final compliances of structures

From the initial results, without optimization, we can verify that the best results were obtained when θ = 45°, the only case in which there was a fiber starting at one of the support points and ending at the load application point. In turn, fibers with an orientation of -45°, before optimization, had an intermediate result, which was better than fully vertical or horizontal fibers.

After the process, the least significant reduction in compliance was for θ = -45°, which was equal to 0.1752 Nm. In comparison with the initial, 0.3048 Nm, it appears that the percentage decrease was 43.41%. For θ = 45°, the final result was much more significant, with a result of 0.0869 Nm. It should be noted that the compliance of this configuration was initially the lowest, so its reduction percentage was not the highest, equal to 68.13%. The slopes with initial configuration of θ = 0° and θ = 90° presented the highest strain energies before optimization among the case studies, respectively 0.3650 and 0.3659 Nm. The final result for the plate with initial vertical fibers was 0.0802 Nm, which is slightly smaller than the compliance of the plate with an orientation of θ = 45°, but the reduction percentage was better, equal to 78.08%.

In turn, the plate with horizontal fibers was the best result obtained in the work, starting with 0.3650 Nm and ending the process with 0.0616 Nm. In this situation, the strain energy reduction was 83.12%. Compared to the worst result obtained, for the plate with an orientation of -45°, the final compliance was 280% lower in the situation where the orientation was 0°. At that time, demonstrating that the efficiency of the optimization of reinforcements using Linear Programming depends directly on the initial configuration of the fibers. Another aspect observed for the 0° oriented plate was that there was no crossing between the filaments, which occurred in all other results. Furthermore, in all situations, the curves had the starting point located over the constraint and the final point at the point of load application.

CONCLUSIONS

The present work applied a variation of fiber placement methodology to find the best placement of three tow reinforcements over a composite plate. As exposed in the case studies, the initial positioning of the reinforcements is particularly significant to the optimization results. With the algorithm used, cases with placements that demonstrate better initial results will not necessarily develop the best results at the end of the process. In addition, in some cases incorrect positioning can cause fiber crossings, hampering the manufacture of the part in some types of processes. Thus, in order to obtain a better final solution, it is important that more than one initial arrangement be tested until a more expressive result is achieved. Aiming at solving this problem, a pre-optimization algorithm could be developed to define the initial positioning with the highest probability of obtaining a configuration as closely as possible to the local optimal.

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