Robotic Weaving Manufacturing of Optimized Glass Fibres Panels

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Abstract. This article presents the development of robotically fabricated and topological optimized fibreglass weaved panels. The process was led under the material intelligence workflow composed of the digital simulation of mechanical behaviour of the component, programming and optimization of the toolpath, and digital manufacturing with a common CNC machine. Through this process, the panels are optimized to minimize the use of material, decreasing the production time, to achieve its maximum mechanical and functional performance within its own design space.

Keywords: Robotic manufacturing, optimization, fiberglass.

1 Introduction

Composite materials offer a wide range of uses in construction, the flexibility to make different shapes, their mechanical properties and extended useful life make them high-performance materials with comparative advantages over other conventional materials -like aluminium and iron. The application of reinforced plastics with carbon or glass fibers have been very successful in the Aerospatiale, and the past years, in the AEC industries, offering the advantage of having the same -and in some cases better - mechanical properties of components for a fraction of its weight (Burry et al., 2020) compared with conventional materials.

These advances had open new design possibilities for architectural components, opening the development of computational design and robotic fabrication processes to manufacture efficient material systems. Buga (Damborsio, et al., 2020) and Elytra (Dörstelmann, 2017) Pavilions, both developed by researchers from the University of Stuttgart, presents a clear path for the integration of design, simulation, and advanced robotic technologies and processes that can lead to non-standard three-dimensional structures, almost impossible to manufacture with common materials and processes because of its precision, energetic and structural efficiency (Burry, et al., 2020).

From a computational design perspective, each fiber can be understood as a vector (Knippers, 2014) where the internal mechanical forces can be homogeneously distributed through the component (Hensel, 2008). Generative Design for topological mechanical optimization in two dimensions of vector forces has been successfully deployed in the Bionic project developed by The Living in 2016, where the goal was to decrease in 30% the weight of an Airbus A320 internal partition. Each of the internal structural bars was optimized and being replaced with a set of small bars with different thicknesses and strength dependents on the mechanical stresses and loads. One of the problems faced was the standardization of the production of each bar of the partitions, making the process complex for a very straightforward problem.

One of the negative aspects of petrol-based composites materials is their harmful impact on the environment for their manufacturing and their low second life extension possibilities after their original use, reducing its circularity. Nevertheless, advanced in the development of reinforced fibers polymers (NFRP), based on lignocellulosic fibers combined with basic digital manufactured formworks as a complementary tool for manual processes like weaving (Dahy, 2019), have been used successfully in the design and fabrication of high performance and -low tech material systems components (Jaafar, 2019). Making the manufacturing process more accessible in terms of equipment, diverse in terms of material and less harmful for the environment.

Both manufacturing technics, manual and advanced robotics, offers a wide spectrum of possibilities for composite materials. The integration of both processes might allow the serial production of personalized prefabricated structural composite components (Hensel, 2012) to replace, for example, partitions or structural walls commonly used in the construction industry with high structural performance, reducing to the minimum its weight, and with less use of energy (Vivanco, 2020).

This research proposes a straightforward computational design and robotic manufacturing workflow to produce energy-efficient and high mechanical performance fiber panels (Dambrosio, et al., 2020) with common digital fabrication equipment like a three-axis milling machine.

2 Methods and processes

As an initial state to develop this research, studies, and selection of materials and their processes to work with were defined. Further steps were held under an iterative and analytical process between digital and physical prototypes.

1. Composite mixture definition: Roving fiberglass filament, polymeric resin recipe composed by initiators, promoters, accelerators and retarders, and support matrix.

2. CNC Weaving tool: Design and development of a custom and universal weaving tool that can adjust to (almost) any CNC Milling Machine that can keep a constant tension over the fiber and wet the fiber with the polymeric resin in a liquid state, in a pultrusion process.

3. Computational design for mechanical simulation and topological optimization based on machine-learning of structural fibers panels.

4. Fabricate physical prototypes with a three-axis CNC milling machine adapted with the custom weaving tool.

2.1 Composite mixture

There are general recommendations as referenced values for the polymer-fiber rigid matrix (Ashland, 2006), but as the curing process is done with ambient temperature, it is necessary to develop empiric tests (Table 1), to ensure stable, comparable, and desired results, due to the different environmental agents that might affect the mixture composed by initiators, promoters, accelerators, and retarders. Also, to include manufacturing variables like the machine movement speed, quantity and density of the vectors, both with a direct incidence over the time variable. Because of this, the initial mixture had an increment on the cobalt naphthenate (CoNAP), calculated to have a stable liquid mixture for approximately 20 minutes.

MEKP wt%	CoNap (6%) wt%	DMA wt%	2,4-P wt%	Time at 25° C min	Time peak min
1.00	0.25	0.00	0.00	21	37
1.00	0.25	0.00	0.05	23	39
1.00	0.25	0.00	0.10	60	74
1.00	0.25	0.00	0.20	180	191
1.00	0.25	0.00	0.30	265	280
1.00	1.00	0.00	0.00	40	120

Table 1. Referential mixtures values used to test proportions of the polyester resin. In grey the final mixture. Original data base for Ashaland, 2006.

The initial mixture of the polymeric matrix tested was composed of Polyester resin as initiator, Methyl ethyl ketone peroxide (MEKP) to 1% as a catalyst, and Cobalt (Co) to 0,1% as an accelerant. The components were mixed in a steel basin which eliminates the risks of melting the polymeric materials produced by an exothermic reaction in the curating phase, which could melt nylon-type fibers (AOC Resins, 2012). The mixture was manually applied to a Roving 2400 JSP fiberglass strand.

The final mixture is a combination of the base resin with CoNAP and at last with the MEKP. The amount of gross polyester completes 100% wt.

2.2 Custom weaving tool

By modifying a common three-axis milling machine to manufacture the panels, the workflow can be applied in almost any laboratory or place that don't have high technological equipment as robotic arms. To standardize the manufacturing process, the custom weaving tool (Figure 1) must ensure the stabilization of the resin mixture and apply a constant and precise moistening (Koustas, et al., 2018) (Kumar, et al. 2019) over the Roving 2400 JSP filament, both requirements were accomplished by integrating the pultrusion process into the tool.

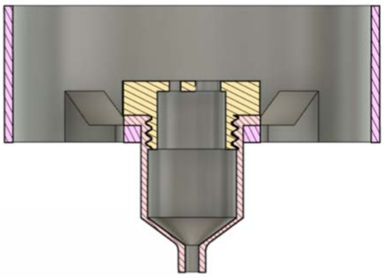

Figure 1: Section view of the moistening tool.

The customised weaving tool replaces the default milling spindle of a milling CNC machine, which will move around a predefined matrix with fixed anchor points, making a weaving movement and depositing the moistened fiber on the matrix.

A resin reserve tank was implemented with a pressure control system composed of a microcontroller, an HK1100C pressure sensor, a 300 psi air compressor, and an optocoupled relay (Figure 2). This adaptation allows manufacturing pieces with a large amount of fiber.

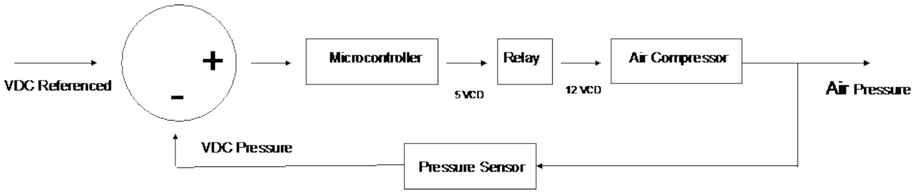

Figure 2: Tank Pressure Control System Diagram.

2.3 Digital Prototypes

Starting from a basic planar panel, the goal was to simulate the application of mechanical loads in different vectors, positions, and fixed vertices (Gil, 2019) (Figure 3). The combination of efforts was applied over three scenarios: first, a vertical load horizontally applied over the total extension of its superior edge; second a combination of lateral and vertical loads in the same geometric plane; and third considering only its weight with a fixed inferior edge (Table 2).

Axis / Force type	X	Y	Z
Compression	0	10kg	0
Flexion	0	10kg	11kg
Neutral	0	10kg	0

Table 2. Compression, flexion and natural applied forces corresponding to each scenario.

Firsts prototypes were done by randomly populating the inferior planar panel and superior edges with fixed points, which once each force was simulated, the edges acted as anchor points, limiting the vector movements through the panel. Setting the border conditions for the simulation. Using a topological optimization algorithm, both mechanical scenarios were tested in addition to a zero forces scenario, evaluating all the possible vectors as a result of the combination of the superior and inferior anchor points.

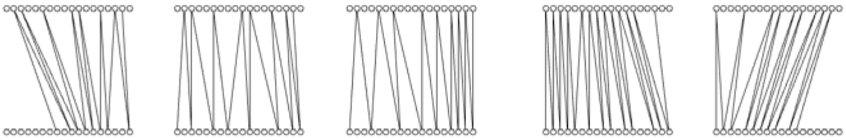

Figure 3. Random vector combinations from the 3.375 possibilities generated with the 15 by 15 points matrix diagram in a zero-force scenario.

Each vector represents a lineal trace of fiber, meaning that the zero-force scenario is a non-performative solution because it is equivalent to 100% of its mass and some fibers will not be under mechanical stress. The optimization goal then is the reduction of the number of vectors, leaving only those subjected to mechanical stress and those which contribute to the distribution of forces.
The selection of the performative vectors was developed by the discretization with points of the resulting graphical diagram, considering the lowest deflection value (Figure 4). In a second step, the outer edges and central axis points were selected, resulting in a clean matrix for the vector - and tool- to pass through.

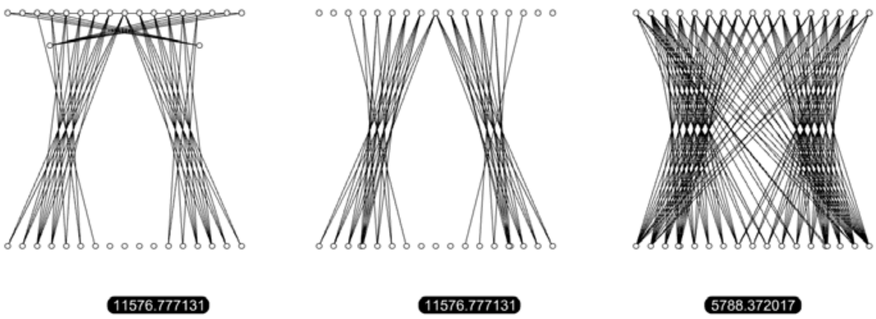

Figure 4: Points extracted from the optimization diagram of vertical forces applied over the horizontal superior edge with lowest vertices as anchor points. The values correspond to each deflection value.

In a 'finite element analysis software, the mechanical properties of the glass fiber were applied to the model, measuring the Von Mises Stress. The values were fed into the topology optimization model to have a distributed and balanced stress over the vectors reducing the displacement and elastic failure (Figure 5).

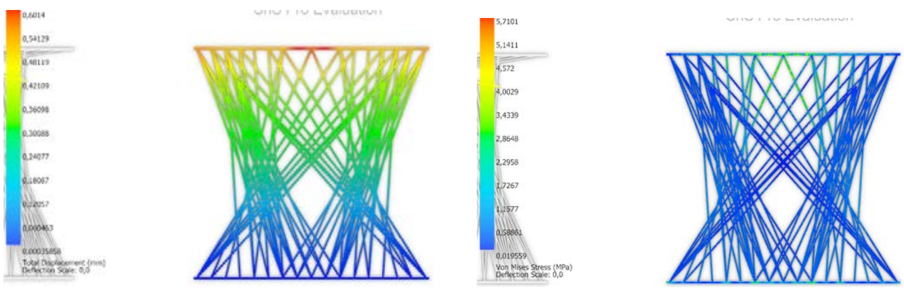

Figure 5. Displacement and Stress analysis diagrams.

Finally, each vector force was converted into polylines, which were sequentially organized and optimized by their length, resulting in a topological optimized array that will the path geometry for the glass fiber and tool.

2.4 Physical Prototypes

First physical prototypes were produced in 40x 40 cms and 80 x 40 cms matrixes (Figure 6), the first with fixed points in the four edges and the second one only in the upper and lower edges. This was done to test the direction and turning radius of the tool that could ensure tension over the fiber and the precision of the fiber direction. Each anchor point represented a point in the simulation and optimization diagrams. Optimized vector lines were converted to a g-code tool path which was loaded to the three-axis CNC machine with the custom weaving tool.

Figure 6. Firsts prototypes. In the left-hand pivots where manually controlled, in the right-hand pivots where adapted in the digital prototypes and toolpath.

3. Results

Final prototypes were fabricated (Figure 7) using the custom tool based on the computational design and optimization workflow described. In the given design and fabrication matrix with all the possible vector combinations, through the optimization process, a limited number of vectors were reduced considerably to achieve a stable mechanical performance of the panel, decreasing the amount of used material.

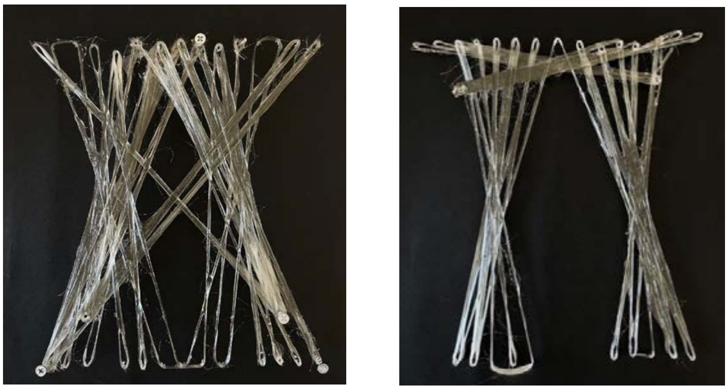

Figure 7. Final prototypes. In the left-hand pivots where manually controlled, in the right-hand pivots where adapted in the digital prototypes and toolpath.

This means that 100% of the used material is performing making the system smart in the sense that there is zero accumulation of non-active material. At the same time, the digital manufacturing process can produce flexible and fast different varieties of panels with a low investment of equipment.

Further Steps

In order to manufacture 1 to 1 scale prototypes, buckling studies and different fiber thicknesses should include in the simulation analysis. Also, measurements of the physical prototypes must be developed to compare them analytically with the digital prototypes

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