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Design of a three-dimensional structure, made of a bio-based material and manufactured using Coreless Robotic Filament Winding (CRFW) technology

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Abstract

The presented work investigates the design and manufacturing of a three-dimensional structure using bio-based materials and Coreless Robotic Filament Winding (CRFW) technology. The primary material is flax, chosen for its sustainability, impregnated with partly bio-based epoxy resin. The study aims to address environmental impact and labor shortages in the construction industry by optimizing the design and manufacturing of a structural element capable of withstanding axial compressive forces. The digital design process utilized Rhinoceros and Grasshopper software, with optimization through Karamba3D and Octopus plugins. Three final design options were manufactured using the ABB IRB 1200-5/0.9 robot, winding impregnated flax rovings into a 3D structure without auxiliary structures. After manufacturing, the structures were post-cured and calibrated using a numerical model in Oasys GSA to simulate the construction process and understand structural behavior during winding and a numerical model in Karamba3D to simulate the compression tests. Axial compression tests on the structures revealed maximum compressive forces of 28.5 kN, 15.34 kN, and 16.69 kN for the three options respectively. Numerical results showed significant differences due to material properties, fabrication imperfections, and test conditions. Despite these differences, the research demonstrates the feasibility of optimized design using robotic filament winding with bio-based flax fibers. Further research is needed to address manufacturing challenges and assess the suitability of this technique for large-scale structural applications.

Keywords: Bio-based materials, Coreless Robotic Filament Winding (CRFW), flax fibers, sustainable construction, digital design, axial compression, (structural) optimization, winding simulation.

1. Introduction

In the modern construction industry, the use of sustainable materials and techniques has become essential to reduce environmental impact and greenhouse gas emissions, as buildings consume up to 40 percent of the world's energy and the construction industry is responsible for half of global greenhouse gas emissions [1]. Governments are accelerating investment in net-zero/low-carbon buildings to achieve the Paris Agreement's goal of limiting global warming to below 2 degrees Celsius [2]. Traditional building materials contribute significantly to these emissions and are often chosen due to their cost-effectiveness and the expertise in their use. A promising solution lies in the innovation of coreless robotic filament winding, particularly using natural fibers like flax, jute, and hemp, which are environmentally sustainable and widely available [3]. This approach addresses the limitations of traditional materials and reduces energy-related pollution. Additionally, the construction industry faces a growing labor shortage, with 28 percent of vacancies in the Netherlands unfilled [4], affecting project timelines and costs. Advanced manufacturing methods such as 3D printing, prefabrication, and robotics, including Coreless Robotic Filament Winding (CRFW), can help mitigate this shortage. Research has shown the feasibility of using bio-based materials in CRFW. For instance, studies at the University of Technology in Eindhoven and at the university of Stuttgart demonstrated the potential of using resin-impregnated sisal rope and natural fibers in robotic winding. This research aims to design and manufacture a three-dimensional structure using bio-based flax fibers with the CRFW technology. The primary goal is to develop a structural element capable of withstanding axial compressive forces, showcasing the feasibility of CRFW with bio-based materials for large-scale applications. The research question is:

"How can a three-dimensional optimized parametric structural element, constructed with bio-based flax fibers, be manufactured using Coreless Robotic Filament Winding (CRFW) technology, and how do structural desk studies relate to lab testing?"

2. Digital Design of The Structure

The University of Stuttgart highlights key factors in designing with filament winding techniques for structures [5] [6]. Robotic filament winding is tension-driven, with fibers spanning between anchor points. To optimize strength, fiber use in tension should be maximized, fiber spans should be reduced through interlocking to increase buckling strength, and adding surface curvature perpendicular to stress direction also increases buckling strength. Given that the final form will be a compressive structural element, failure modes, particularly buckling, must be considered. Euler’s formula for critical load of a simply supported column is relevant here. The structure's critical length is one meter. For coreless filament winding, shape studies focusing on anticlastic shapes are essential.

Research by Bodea S. et al. [7] applied a coreless multi-layered fiber system, used in the Buga fiber pavilion, where a weak glass fiber layer forms a lattice surface, on which stronger carbon fibers are winded. The design begins with defining the global geometry from boundary frames and winding pins, followed by simulating the glass fiber lattice and projecting the carbon fiber layup. See figure 1 for the composition of the coreless multi layered fiber system.

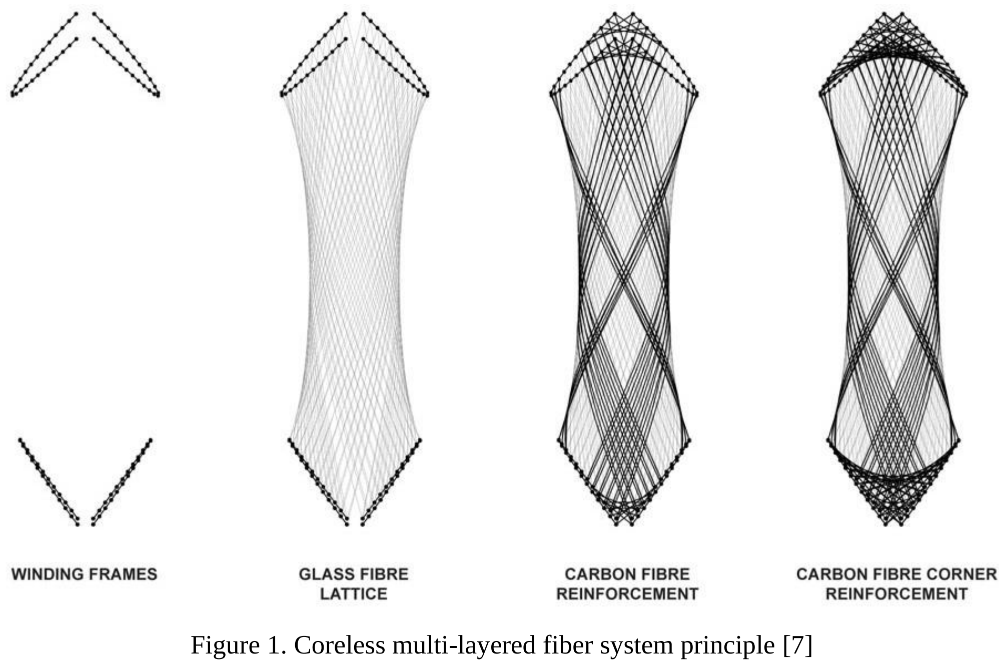

Figure 1. Coreless multi-layered fiber system principle [7]

2.1. Design of The Structure

The digital design is executed using Rhinoceros and Grasshopper (RG). The initial stage involves finding the shape of the structure, specifically a hyperboloid, using the skew line principle. This involves constructing two base curves, segmenting these through points, and creating skewed lines that form a hyperboloid. The first winding sequence, or the 'lattice layer,' forms the base for subsequent layers. The hyperboloid structure is transformed into a surface of revolution, serving as the base for the 'reinforcement layer,' created by diagonal (spiral) lines using the NURBS-based methodology [8]. These diagonals are generated using Python in RG, ensuring optimal spiral patterns. The diagonals are 'locally geodesic,' behaving like the shortest path within segments but forming a spiral when considered across the entire surface.

A Python script calculates diagonals for various angles, ensuring precise endpoints for winding pins. The script gathers data for 11 to 16 points to optimize contact points and robot movements. The model in RG, recognizing deviations from reality, is used mainly for manufacturing of the structural elements, with the final structure calibrated against a numeric model. This approach allows for generating various design variations shown in figure 2.

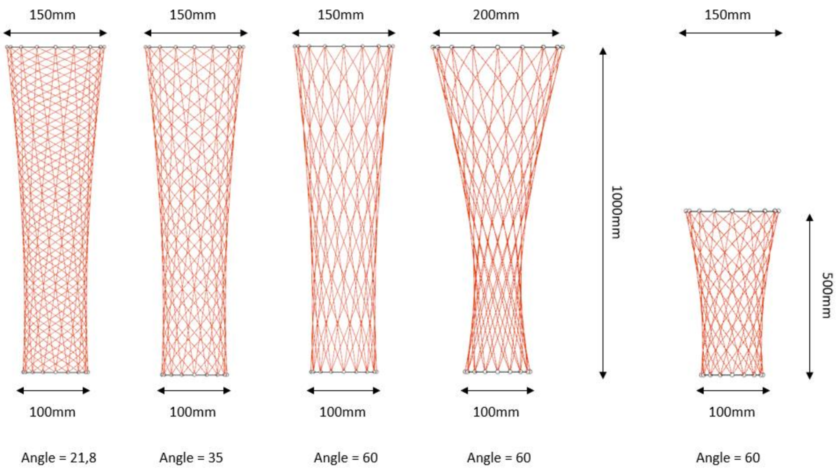

Figure 2. Possible design variants of geometrical model

2.2. Optimization of The Design

Slender structures loaded in compression are prone to buckling. Research by L. Krijnen [6]indicates that synclastic constructions enhance stability. However, filament winding a synclastic structure is impractical without a core or auxiliary parts. Therefore, a shape study was conducted to determine the optimal form for coreless filament winding.

2.2.1. Shape Study and Buckling Analysis

Three shapes were tested: a traditional circular column with no curvature, an anticlastic shape and a combination of two anticlastic shapes forming a synclastic shape. The surface area of each shape was kept constant, and their buckling factors (Bfacs) were calculated using Karamba3D under a 1 kN load. The anticlastic shape showed better performance against buckling, especially when considering material properties and manufacturing techniques, which often lead to local buckling in filament-wound structures. Further comparison of anticlastic and combination shapes, maintaining a consistent fiber mass, showed that the anticlastic variant performed better. Mainly because on surface level the anticlastic version gathers more material at the weaker point of the structure.

2.2.2. Optimization and Final Design

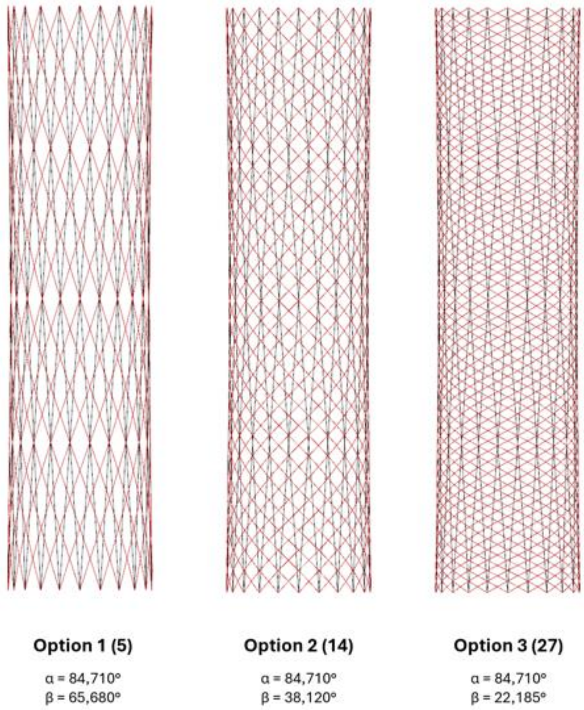

Figure 3. Final design options

Three final design options were optimized using the Octopus plug-in for Rhino Grasshopper, focusing on maintaining uniform fiber length across designs. The optimal designs included varying angles of the diagonal reinforcement layer. To ensure the same fiber mass is used for each option, the option requiring the least amount of fiber will be winded more times than the other options. This process is visually represented in Figure 4. The total fiber length for the reinforcement layer of each structure was approximately 93 meters, ensuring consistency in mass across all design variants.

Figure 4. Visual representation number of windings

2.3. Output and Translation to The Robot

Final design options for the structure were established. To manufacture via coreless filament winding, an Euler path is needed. The Leafvein plug-in defined this path using a 'Custom Graph' component, which built a graph from design line segments. The generated path ensured the lattice layer is wound before the diagonals to maintain structural integrity. Adjustments were made to wind mirrored diagonals consecutively, avoiding asymmetry. The path included semicircles around winding points for smooth robot navigation. Using Rhino Grasshopper's Robot Components (RC), the path points were input into the RC script. The robot's nozzle and 'turning table' were calibrated, and start/end points were set to avoid collisions, starting 10 cm above the first point. The robot followed the path with a consistent speed of 100 mm/s, ensuring optimal movement alignment. The 'Path Generator' simulated the robot's path, and the 'RAPID Generator' created scripts for robot movements and head orientation. These were validated in Robot Studio to ensure error-free execution, preparing the RAPID code for production.

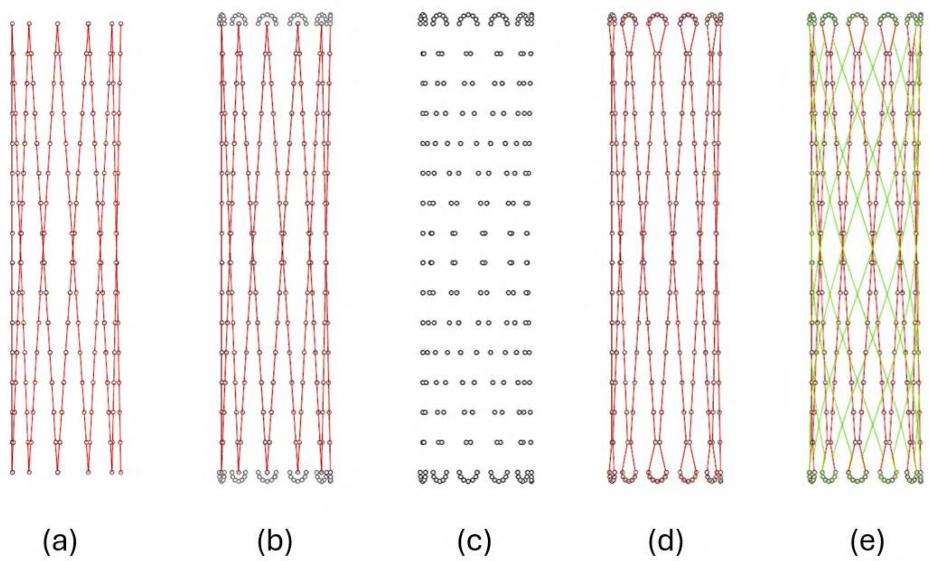

Figure 5. Generation of robot path

3. Materialization

This research explores bio-based flax fibers for structural applications due to their high potential in previous research [3]. Flax, grown in the Netherlands, Belgium, and France, can be cultivated for linen fibers or linseed oil. The process to obtain flax fibers involves sowing, pulling out the plant, retting, breaking the stem, scutching, and hackling to refine the fibers [9]. Because flax fibers are made from plants, the size and quality of fibers can be affected by environmental conditions such as growth, location, nutrients, temperatures and seasons. The Depestele FR 2400 flax fibers, with a tex value of 2400, are used for this project due to availability, which are characterzed as flat rovings. Flat rovings from flax fibers offer better mechanical properties, improved resin impregnation, and fewer voids compared to twisted rovings [10]. InfuGreen 810 bio-based epoxy resin system with SD 8824 hardener, selected for its compatibility and previous use in similar studies, is employed.

3.1 Material Properties

To compare the experimental results with the model simulations, it is important to understand the material properties of the final composite. For a unidirectional composite, where all fibers are aligned in the direction of the applied load, the stiffness can be estimated by considering the structure as a simple beam. This assumption implies that the two components are perfectly bonded and deform together. The Voigt estimate or rule of mixtures [11] can be applied to determine the longitudinal elastic modulus of he composite. In examining the literature and previous projects involving natural fibers in composite structures, several key points emerge from the paper by Marta Gil Per´ez et al [3], cited: The calculation is reduced to 70% of the original rule of mixtures based on previous CFW project experiences for three main reasons. Firstly, the rule of mixtures assumes proper bonding between fibers and resin, which is often not the case in CFW structures due to the presence of voids in the bundles. Secondly, the components are subjected to high compression loads, and the compression stiffness of a unidirectional composite is known to be lower than its tensile stiffness, leading to unpredictable structural behavior. Thirdly, the FVR must be estimated from small-scale specimens, which may differ from the final large-scale component, and deviations in the assumed FVR will reduce the resulting stiffness. Therefore equation 6 changes into equation 7, where this 70% reduction is implemented. This leads to the original formula as given in the Livmats pavilion research [3]:

$$Ec = 0.7 \times (Ef \times FVR + Em \times (1 - FVR))$$

4. Manufacturing of the structure

The structure is manufactured through Robotic Coreless Filament Winding (RCFW). The manufacturing set-up replicates elements from previous projects [6] incorporating an ABB IRB 1200-5/0.9 robot, a threaded rod with a bearing nut, new aluminum end plates with winding pins, and a turntable, which is shown in figure 6. Upgrades to previous projects include a stiffer M16 threaded rod to prevent bending during manufacturing and an improved connection to the rotation table. The aluminum end plates were optimized for better strength and stability. The design features 248 mm diameter plates positioned one meter apart on the threaded rod. Additional holes allow for reinforced rods if needed. Winding pins, designed with bolts, sleeves, and washers, minimize friction and prevent fiber slippage. A redesigned end-effector with an adjustable aluminum tube and a securely attached ceramic ring was introduced to enhance performance and prevent fiber damage. A revised resin bath setup with steel corner profiles and adjustable rollers was used for fiber impregnation. Preliminary tests with flax fibers and SR Infugreen 810 epoxy resin showed effective impregnation and composite fabrication. Before manufacturing the flax fibers were dried at 40°C to reduce moisture content from 8% to below 5%, ideally 2-3%, to improve fiber-matrix adhesion and prevent cavity formation during curing.

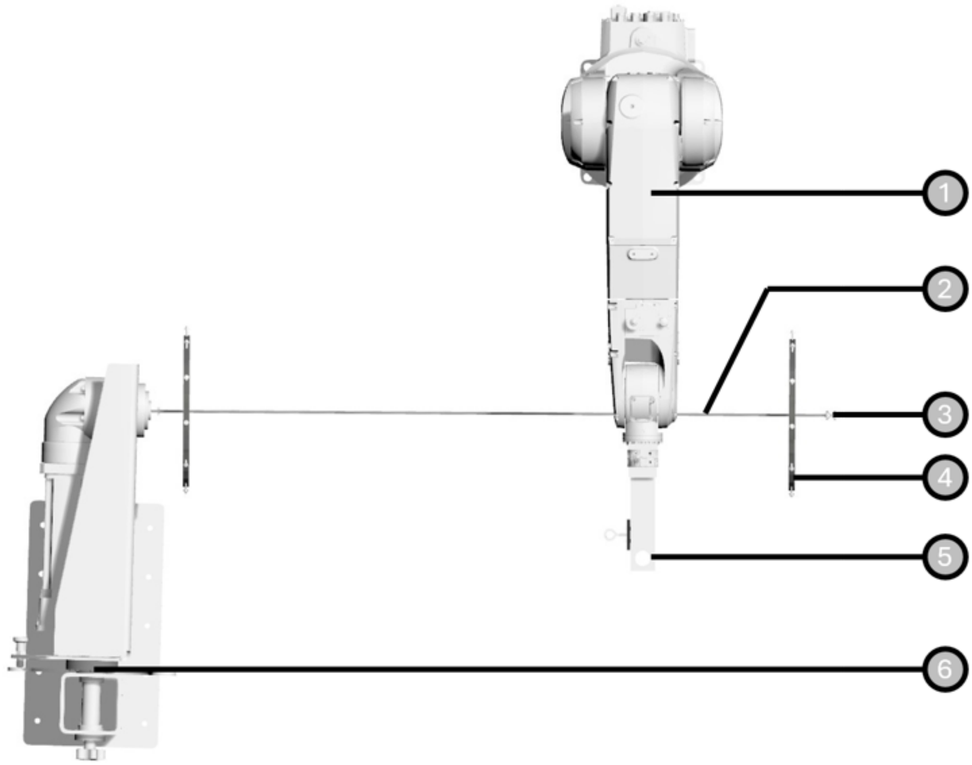

Figure 7. New manufacturing process set-up: (1) ABB IRB 1200-5/0.9 robot (2) Threaded rod (3) Supportof threaded rod with bearing nut (4) New aluminium end plate with winding pins (5) New robot end-effector (6) Rotation external axis (turntable).

4.1 Robotic Coreless Filament Winding

The winding process involved impregnating flax rovings with epoxy resin, assembling them into a bundle, and guiding the bundle around winding pins. Initial tests with sisal ropes identified issues with the end-effector and fiber tension, but validated the robot path and the set-up. The first winding test with flax rovings revealed issues with the ceramic ring and fiber angles. Adjustments included securing the ring and modifying the end-effector angle. Positioning bobbins vertically also improved the process. After manufacturing, the structures were cured at ambient temperature and at 40°C for eight hours. This ensured proper hardening and structural integrity. The final structures, displayed in figure 7, were evaluated for weight and fiber length consistency. A comparison with the theoretically expected total length of roving required to generate the design showed that this generation is a valid generation and that the designs could be compared based on their mass.

Figure 7. Final fabricted composite elements

Figure 7 shows the four manufactured structures after the internal formwork is removed. It can be seen that the structures feature some imperfections, V101 is the test version in which the ceramic ring got stuck. Where V2O1 is the best manufactured structure without imperfections. V1O2 and V1O3 have hardened loose ropes, which will affect the testing capacity.

5. Numerical Model and Testing

For numerical analysis, the design is converted into a GSA model using the GSA plugin for Rhino Grasshopper. This model simulates pre-tensioning of the winding lines in a staged construction, reflecting the actual robotic winding process. The GSA model divides winding lines into groups and uses staging analysis to simulate various phases of fabrication. Several assumptions were made during the modelling process. First, it was assumed that each winding line undergoes equal pre-tension, despite potential variations caused by factors like material inaccuracies and robot precision. Second, the model assumed perfect bonding and alignment of the 3D elements, simplifying the complex interactions between individual. The coreless winding process was monitored to analyse deformation, with comparisons made between GSA model stages and actual winding outcomes. This validation process, shown in Figure 8, confirmed the accuracy of the simulation for Option 1. Where every stage represents the addition of a diagonal. The behavior of the structure is described by the axial force in the winding lines. Since the values of the prestress are not known, No actual values were used. In the GSA model, each node relates to a cut element, resulting in a diagonal and a lattice consisting of multiple elements. It is important to understand the distribution of forces within these different elements. Therefore, for a diagonal and a lattice element, all relevant information is extracted from the GSA model. Figure 9 shows the composition of the first diagonal and an element of the lattice layer in the GSA model. This information of the model is represented in a 2D bar graph, where each element is projected with the corresponding force in each stage. This is shown in figure 9.

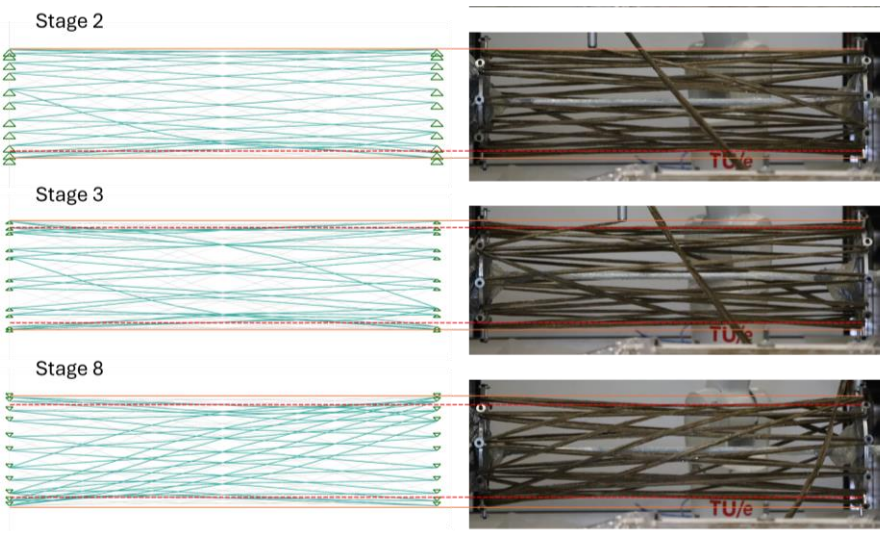

Figure 8. Comparison GSA model and reality

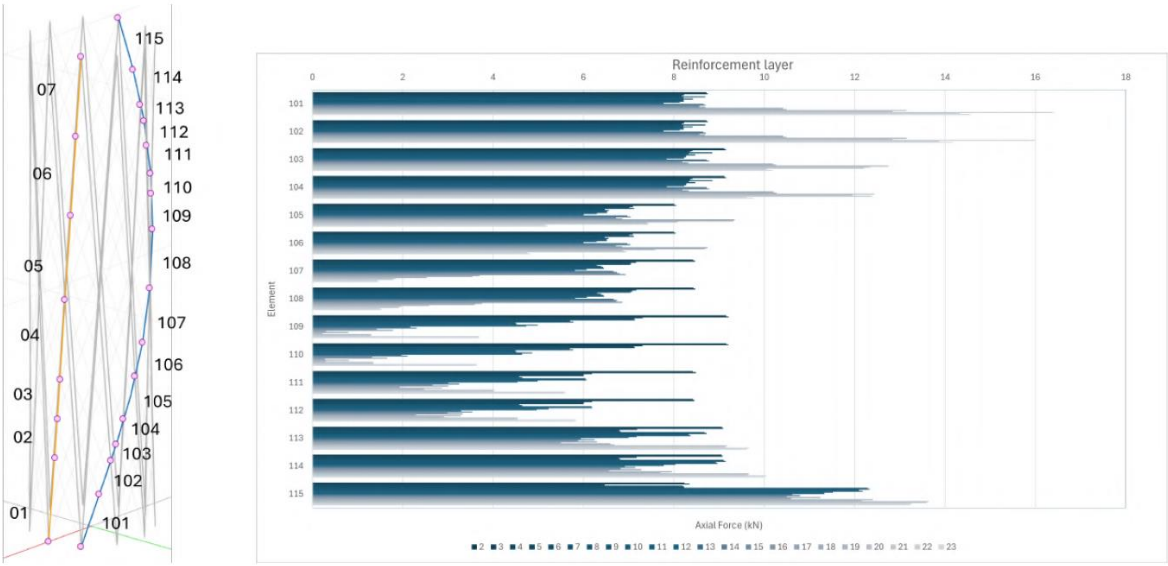

Figure 9. Staging analysis results

The hypothesis states that the lattice layer will experience an increasing axial force as it is pushed inward by the reinforcement layer, increasing the tension in this winding line. Conversely, the behavior is different for the first diagonal. As the diagonals deform the structure with each additional layer, the tension in the first winded diagonal decreases. This hypothesis is supported by the model for the lattice layer, as illustrated in Table 12, where the average force in the lattice and the diagonal is taken into account. Every stage represents the addition of a new diagonal. Table 1 shows the average value of one element of the lattice layer and one diagonal. However, for the diagonal, it can be seen that the average force increases in later stages. This is caused by the bottom and top elements (101/102 and 114/115), which get a very high axial force. where in the middle element, this force is constantly decreasing.

Table 1. Average axial force in elements.

Stage	2	3	4	5	6	7	8	9	10	11	12
Element 1 (kN) (Lattice layer)*	2.43	2.452	2.69	2.68	5.15	5.16	6.62	6.59	7.82	7.69	7.66
Element 2 (kN) (Diagonal)*	8.64	8.69	7.25	7.36	7.50	7.59	7.69	7.59	7.61	7.23	6.94
Stage	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Element 1 (kN) (Lattice layer)*	7.48	7.43	8.86	8.87	8.77	8.80	8.81	8.87	9.009	8.98	9.89
Element 2 (kN) (Diagonal)*	6.66	6.79	6.41	6.72	6.56	7.12	7.31	7.84	8.27	7.88	7.92

Since option 1 involves no loose rovings during the winding process, there is no compression in the winding layers. This model can be used to simulate the behavior of the rovings, specifically to determine if they will remain under tension and avoid ”buckling” due to potential compression. By running a simulation on the design, it can be assessed whether the rovings will stay in tension without becoming loose.

5.1 Numerical Model Compression Test

A numerical model was developed using the Karamba3D plugin in Rhino Grasshopper to perform finite element analysis on parameterized geometric models. The initial geometric model, consisting of lines and points, was converted into beam elements with nodes containing physical properties. Several assumptions were made, such as considering all intersecting points as fixed nodes. Material properties and cross-sections from Table 2 were incorporated, and rigid elements were added to the top and bottom of the structure to act as end nodes. Boundary conditions were defined using the 'Beam-Joint' component, which allowed rotation and limited translation. Supports were added to the center of the rigid elements: the bottom support restricted translation in all directions while allowing rotation, and the upper support restricted translation in the X and Y directions and rotation in the Z direction. The structure was axially loaded with a 1 kN point load, transferred via rigid elements.

Table 2. Calibration of numerical model.

Specimen	V1O1	V2O1	V1O2	V1O3
Lattice layer (mm) (width x depth)	10 x 5	10 x 5	10 x 5	10 x 5
Reinforcement layer (mm) (width x depth)	30 x 5	30 x 5	20 x 5	12 x 5
Inward deformation (mm)	30	30	40	50
Elastic modulus fibers (GPa)	55.1	55.1	55.1	55.1
Elastic modulus matrix (GPa)	3	3	3	3
Elastic modulus composite (GPa)	13.21	14.77	13.68	11.06

6. Compression Testing of Fiber Composite Structures

Four fiber composite structures were tested in axial compression using the Instrom compression testing machine in the SED lab at TU/e. The structures were simply supported, allowing rotation but preventing movement, with aluminum plates used to distribute the load evenly across all bundles. Spherical hinges and steel plates ensured uniform axial pressure distribution. A tensile wire sensor measured vertical displacement, producing force-displacement diagrams.

6.1 Results Compression Test

Compression test V1O1**:** This test structure, damaged during the winding process, reached a maximum force of 23.64 kN. Failure was observed at the winding pins, with buckling at the top of the structure.

Compression test V2O1**:** This structure, visually the most efficiently manufactured, achieved a maximum force of 28.49 kN. Failure occurred due to individual bundle buckling and delamination of the lattice and reinforcement layers.

Compression tests V1O2 and V1O3**:** These structures, which had imperfections from the winding process, performed poorly. V1O2 failed similarly to V1O1, while V1O3 showed no clear failure point, likely due to internal bundle buckling.

6.2 Comparison with Numerical Model

Table 3 compares the maximum compressive forces from physical tests and numerical models. The physical tests showed significantly lower compressive forces compared to numerical models, due to factors like idealized material properties, manufacturing defects, and differences in test setup and boundary conditions. Improving material characterization and addressing manufacturing inconsistencies are crucial for accurate predictions. In conclusion, option 1 performed best due to better bonding between layers, reducing the likelihood of separate element buckling and structural failure. However, the manufacturing process needs optimization to eliminate loose bundles and enhance structural integrity.

Table 3. Comparison test results and numerical results.

Specimen	**Max Compressive Force [kN]**	**Max Force in Numerical Model [kN]**	**Factor Difference**
V1O1	23.64	68.69	2.91
V2O1	28.49	68.69	2.41
V1O2	15.34	114.21	7.45
V1O3	16.69	216.32	12.96

7. Discussion

The comparison between test results and numerical model predictions for axial compression tests reveals significant differences. The observed compressive forces in physical tests may be lower than predicted due to:

- Material Properties and Assumptions: Idealized properties and simplifications in the model do not accurately reflect actual material behavior, quality, or manufacturing inconsistencies.
- Fabrication Errors: Manufacturing defects like voids and incomplete fiber impregnation are not accounted for in the model.
- Test Setup and Boundary Conditions: Differences in load setups and boundary conditions between tests and models contribute to differences.

Improving numerical model accuracy requires extensive material characterization and addressing manufacturing inconsistencies. Tests must closely match model calculations. Option 1 is preferred due to better structural depth and bonding between layers, crucial for preventing buckling and structural failure. Manufacturing issues prevented the optimization of options 2 and 3. Using flax fibers advances sustainable construction but is limited by the resin being only 38% bio-based. A fully bio-based resin is needed for true sustainability. The process generates waste and excess resin. CRFW technology reduces waste and enables complex geometries but faces challenges like consistent fiber tension and resin impregnation. More iterations are needed to resolve these issues. Improving the fiber volume ratio (FVR) is necessary for high-quality composites. Practical applications face challenges with resin pot life and robot reach, suggesting connecting smaller elements as a solution.

8. Conclusion

This research project focused on using biobased materials and Coreless Robotic Filament Winding (CRFW) technology to create a one-meter-tall structure. Flax fibers with bio-based epoxy resin were used to address environmental concerns and labor shortages in construction. The design process utilized Rhinoceros, Grasshopper, Karamba3D, and Octopus plugins to create optimized anticlastic shapes. A winding path was simulated in Robot Studio, and the ABB IRB 1200-5/0.9 robot performed the winding using Depestele FR 2400 flax rovings and InfuGreen 810 epoxy resin. Four structures were manufactured and analyzed. Testing showed local buckling, revealing discrepancies between numerical predictions and actual outcomes. The study confirmed the feasibility of using bio-based flax fibers in CRFW. Further research is needed to improve accuracy and scalability, focusing on material characterization and enhanced production tools. This project highlights the potential for sustainable construction using CRFW technology and biobased materials.

9. Recommendations

Reflecting on the design and testing process, several areas require further research. First, while bio-based flax fibers were used to reduce environmental pollution, the epoxy resin was only 38% bio-based. Future studies should explore fully bio-based options like Oribond by Orineo for better sustainability. Improving material properties and the filament winding process is essential. This includes better impregnation of flax fibers with bio-based epoxy resin and optimizing winding techniques for consistent structural properties. Comprehensive testing will help understand the long-term performance and durability of these materials. Enhancing the accuracy of numerical models used to simulate manufacturing and predict structural behavior is crucial. Aligning physical test conditions more closely with model assumptions will improve reliability. Additionally, integrating advanced tools like a robotic end effector for measuring pretension and an impregnation end effector can enhance research and production quality, ensuring precise control and reducing waste. Addressing these areas can advance the field of filament winding technology, promoting sustainable and efficient construction practices.

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