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Co-Design of Fibrous Walls for Multi-Story Buildings

Abstract: Coreless filament winding (CFW) is an advancement of industrial filament winding for architectural applications. In this process, the formwork is reduced to an absolute minimum, allowing the fibers to span freely in space between anchor points. Using carbon and glass fibers with a resin matrix, it exhibits high potential for lightweight, material efficient building elements. While previous research demonstrated its applicability in shell, roof and long-span structures, the potential in using this method for multi-story wall and slab systems has not been thoroughly investigated. This paper elaborates on methods to develop structural wall components built entirely of carbon and glass fiber composite, which are specifically tailored to meet the requirements of multi-story construction in architecture. A computational design method based on tangent-based approximation was developed to generate bespoke fiber patterns and openings, allowing the wall components to act as load-bearing elements. This facilitates the generation of a multitude of pattern variations which can be adapted to axisymmetric and asymmetric boundary conditions. Structural performance of the building elements is evaluated throughout the design process by means of finite element analysis establishing a feedback loop between design, robotic fabrication and structural evaluation and informing the optimisation of the wall geometry and fiber layup. The developed methods were successfully applied in the design and fabrication of a multistory fiber installation exhibited at the 17th Architectural Biennale in Venice. It demonstrates the potential of coreless wound load-adapted fibrous walls as architectural building components leveraging integrative computational design, structural engineering and robotic prefabrication.

1 Introduction

1.1 Coreless filament winding in architectural design

Coreless filament wound structures (CFW) are lightweight fiber composite elements characterized by their low intrinsic weight and material- fficient fabrication method (Menges and Knippers 2015). Using industrial robots and an external rotation axis, fibers are robotically placed on a winding frame at structurally relevant locations during fabrication (Gil Pérez et al. 2021). This can be achieved by winding the fibers around anchor points on the frame, which secure their final position in the structure (La Magna

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et al. 2016), as well as by digitally planning the placement order of the structurally informed fibers along these anchor points and developing a matrix that ensures as many fiber iterations as possible. The fiber layup is designed based on the definition of the sequence of connection points which is referred to as fiber syntax. In essence, the alignment of the fibers to the direction of the loads as well as their interaction between each other makes the fibers structurally efficient. The component geometry also plays a crucial role in the performance and material efficiency of the structure; they are directly linked to the finished form of the physical component, which in turn means that deviations and tolerances from the digital model must be kept as low as possible (Reichert et al. 2014). Computational design simulations and form-finding methods make it possible to develop genuinely digital building systems (Knippers et al. 2021) and to digitally simulate and predict the final shape, the fiber interactions, and the corresponding physical influences of the winding process (Menges et al. 2022).

Fig. 1: Overview of the full installation of Maison Fibre © ICD/ITKE/IntCDC, University of Stuttgart

The coreless filament winding method builds on more than a decade of research in fiber construction by ICD and ITKE at University of Stuttgart and its application was successfully demonstrated through multiple research projects. The variation of different numbers of anchor points along non-identical frames enabled the fabrication of non-circular, non-uniform fiber bodies in the ICD/ITKE Research Pavilion 2013-14 with different numbers of anchor points (Dörstelmann et al. 2015). The Elytra Filament Pavilion (Koslowski et al. 2017) enabled the production of fiber components with circular apertures, which was achieved with identical frames and identical number of anchor points. The BUGA Fibre Pavilion incorporated a method for the syntax development of an interlaced fiber pattern with adjustable shift values, which allowed for the variation of the component's geometric properties (Dambrosio et al. 2019, Zechmeister et al. 2020), which can be applied to different densities of fiber layups in the fiber composite dome structure (Gil Pérez et al. 2020). Previous research outcome serves as the base for the development of visually permeable yet structural fibrous wall elements as shown in Fig. 1. The geometry of the wall component is a result of reciprocal effects between architecture, structure and fabrication. With coreless wound structures their final shape is determined by the material's behavior during fabrication. Through the sequential process of CFW, fiber interaction determines the material limits that form three-dimensional geometries and ensures structural performance. The more three-dimensional the structure, higher the chances to achieve good fiber interaction.

1.2 Co-Design of Maison Fibre

Co-design of fibrous architecture can be understood as an interdependence between the CFW fabrication process and the resulting design and performance characteristics, and are the result of a feedback-based development of design and engineering methods, fabrication processes and the resulting material and building system (Menges et al., 2022). As part of the continued research in the field of robotically fabricated CFW structures, this modular building system not only performs as a cantilevered canopy or skeletal dome, but extends the application of CWF towards multi-story architectural structures (Dambrosio et al. 2021).

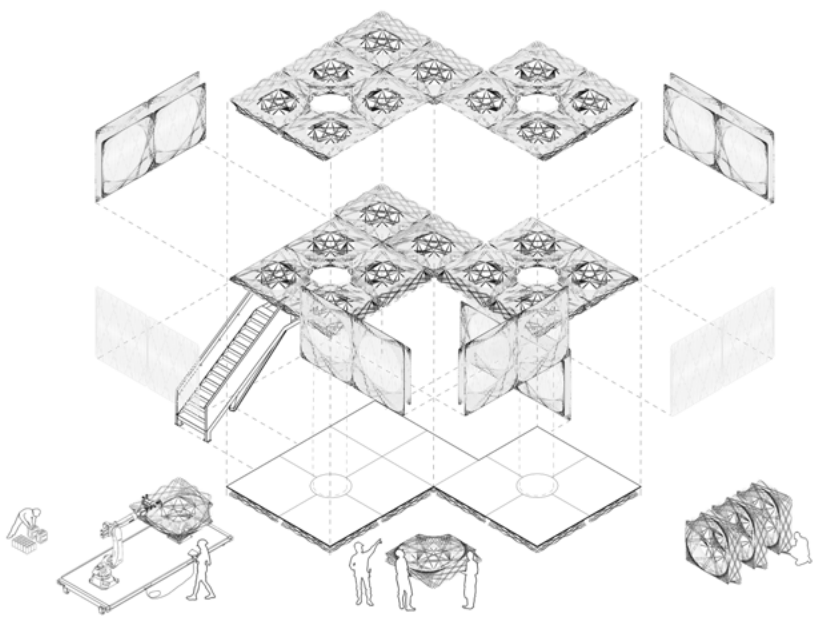

Fig. 2: Modular Building System of the installation © ICD/ITKE/IntCDC, University of Stuttgart.

Here a two-story FRP timber hybrid building was developed for the 17th Venice Architecture Exhibition, which consists of 30 modular arranged components, as shown in Fig. 2, that correspond to the conventional 2.5×2.5 m grid of multi-story structures (Dambrosio et al. 2021). The 20 slab and 10 wall components use a reconfigurable frame to accommodate all component variations and their fiber layup corresponds to specific requirements based on individual tributary loads (Gil Pérez at al. 2022a). This paper focuses on novel computational design exploration strategies of fibrous wall elements. These components are structurally relevant parts of the installation and integrate both building opening, vertical bracing and fall protection within identical boundary conditions that originate from one specific frame configuration.

2 Background

The research paper focuses on the design development of the fiber wall components. Novel criteria to the design of fiber components had to be examined: Instead of using bespoke boundary configurations, as in the BUGA Fibre Pavilion (Bodea et al. 2020) or identical frames for the Elytra Filament Pavilion (Dörstelmann et al. 2017), here a set of individual boundary frames had to be used for the articulation of individual geometries within this boundary condition. The aperture, which is a prominent detail of the component, usually originates from a regular shift of anchor points in the syntax, where two continuous frames with identical numbers of anchor points lead to a uniform-shaped aperture that acts as a fiber body.

For Maison Fibre, both continuous frames and the number of anchor points are not identical. This led to an investigation of scaffolding strategies for uniform apertures in a non-uniform boundary system. A key challenge for the design development of the wall component was the smaller, square-shaped frame, coming from a rigid global configuration, as it allows for the production of both walls and slabs. This configuration in combination with a larger, non-uniform secondary frame, had to be geometrically transformed so that it allows for a high degree of fiber interactions in the context of CFW. The wall components consist of three main elements:

1. The glass fiber screen, which is located on the outside of the component and acts as enclosure and as fall protection
2. The inner fiber body, consisting of a glass fiber scaffold, and a carbon fiber reinforcement layer in distinct locations to provide structural strength and stiffness
3. The outer fiber body which adds to the structural performance of the component and incorporates both glass fiber body and carbon fiber reinforcement layers.

For the structural articulation of the wall components, a distinction was made between ground floor and upper floor components, which is reflected in the amount of material used. Two wall components are always placed next to each other, and the layup is mirrored vertically. The structural requirements of the wall component relate to the design of the carbon fiber layup and the distribution of the connections between slab and wall, and wall to wall. The layup needs to respond to the load transfer between connection points informed by structural FEM. From an architectural design standpoint, it was intended to create elliptical shapes for the apertures, allowing for window-frame-like configurations in the wall components.

In the BUGA Pavilion 2019 (Zechmeister et al. 2020) or the Elytra Filament Pavilion (Dörstelmann et al. 2017), a shifted syntax was considered for the development of a scaffolding layer that is used to add reinforcement in the fiber components. Typically, the reinforcement layup needs to be continuous to transfer loads between components. The more this syntax shift differs from the starting point of the initial list, the smaller the aperture inside the component becomes. This usually leads to a uniform shape of the aperture with a uniform distance to the edge in a component with identical frames. The challenge in the wall components is to establish a strategy for different shapes and numbers of anchor points of the two main frame pieces to create a homogenous aperture shape with a high degree of fiber interactions. Typically, this would rather lead to an irregular aperture. Moreover, if the number of anchor points on one side of the frame are different than on the other, this can cause less fiber interactions in the component that is based on the interlaced syntax method, leading to a structurally undesirable result. In this project, a slab component was tested and used for the calibration of the other component types (Gil Pérez et al. 2022a).

3 Methods

The two winding frames used for the wall components are not identical: Since the floor and ceiling components are connected to the wall components at an angle of 45 degrees, one of the two winding frames had to be smaller. As a result, there is a larger frame with 106 anchor points of 10 cm distance and a smaller frame with only 94 anchor points, sharing the same distance, which is used for a multi-layered configuration of a wall component (Fig. 3).

The structural design of the building system combines multi-level FE modeling with a digital-physical approach that has been used in recent CFW structures (Gil Pérez et al. 2021; Gil Pérez et al. 2022b). This allows to evaluate the structural performance and global load distribution with a full FE model, anddesign the specific fiber layup for the carbon reinforcement layers in a component level (Fig. 4). To complement this approach, calibrate the structural simulations, and prove the integrity of the structure, full-scale prototyping and mechanical testing is performed for a single component type. The co-design of the wall components (Fig. 4) underwent two feedback loops: Firstly, the glass fiber body was investigated with a syntax strategy to obtain the desired geometry. This was then evaluated with a surface FEM giving geometrical feedback

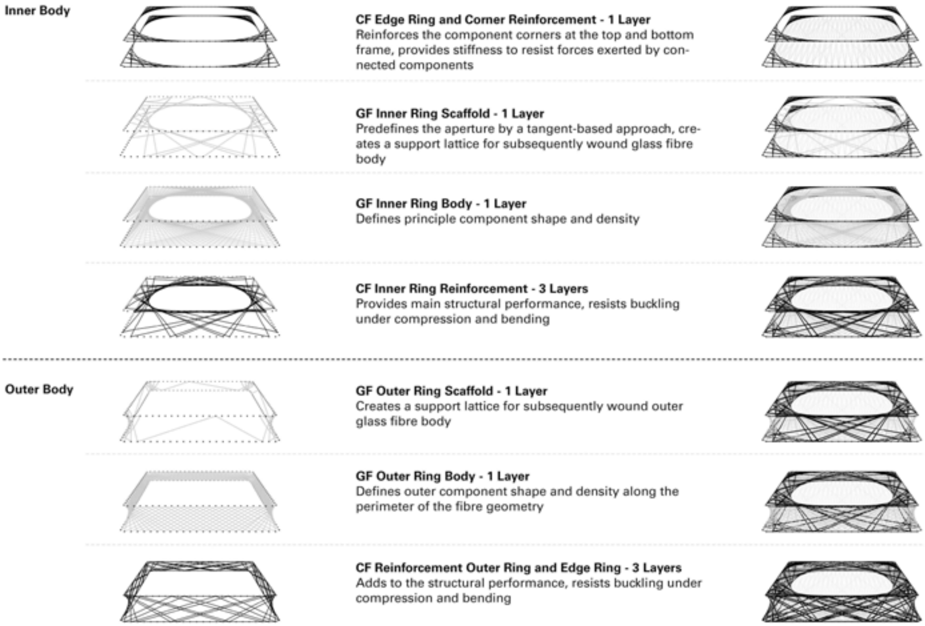

Fig. 3: Layer configuration of the fiber wall bodies.

to the design. Then the carbon fiber reinforcement was designed through a second iterative loop where a beam FEM representing the carbon fibers was used to investigate the fiber layup yielding best structural performance.

3.1 Inner and Outer Glass Fiber Bodies

Due to the required stiffening of the walls within the overall composition of the structure, as well as the specific load bearing capacity that the walls need to fulfill, a uniform fiber body had to be introduced to transfer the loads evenly to the adjacent components. As a consequence, the aperture also had to be uniform, even though the number of anchor points and frame size were different. Here, a new method for the generation of the fiber body syntax was developed, shown in Fig. 5.

For the wall components, a planar contour was defined in the central field of the frames, which is to describe the glass fiber aperture. In the next step, the subdivision of this contour was defined based on the specific distances to the frame edge, which will become an approximation for the aperture of the fiber body. Subsequently, the tangent at the subdivision points along the contour curve can be generated, which provides information about which anchor point can be reached on the corresponding frame at the position of the contour. Using this method, the resulting aperture can be developed using tangents from the central contour, displayed in Fig. 5.

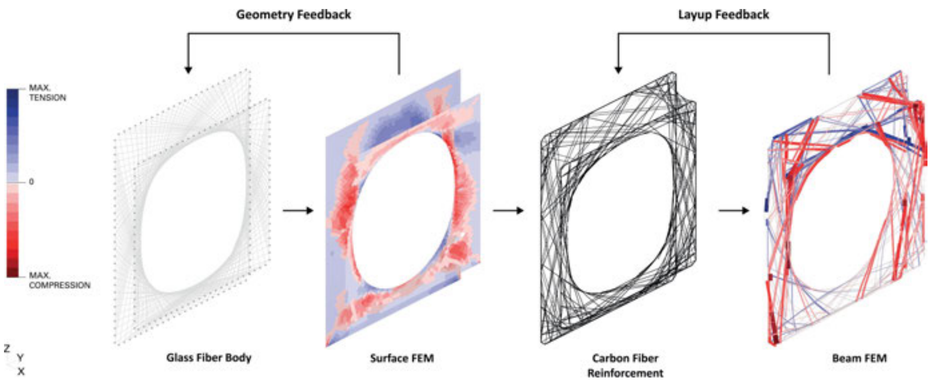

Fig. 4: Co-Design of fibrous walls based on FEM feedback loop.

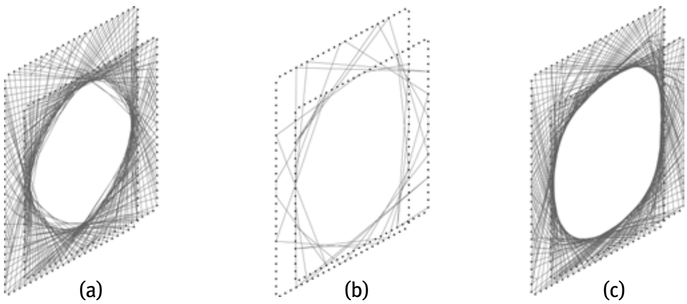

Fig. 5: Inner Ring Body Aperture: Difference between an interlaced shift syntax for asymmetric frames with and without a tangent-based scaffold layer; visualized from fiber net simulations. (a) Inner ring body syntax without a scaffold layer results in a non-uniform aperture with loose fibers (b) Tangent-based scaffold layer (c) Uniform inner ring body syntax based on identical interlaced shifts from (a) but with a precedent tangent-based scaffold layer (b).

As the frames are different and have a different number of anchor points, the aperture does not necessarily correspond to an axisymmetric geometry when all anchor points are used for the fiber layup. To avoid this, the so-called scaffold layer was introduced to the multilayer structure of the fiber body, which creates a syntax with as few tangent fibers as possible to constrain the shape of the subsequent fiber body (Fig. 6). This approach is an approximation of the final shape: since not every tangent along the inner contour curve meets an anchor point along the planarized frame, small deviations must be accepted. The maximum deviation of the component corresponds to the anchor point distance.

Additionally, the strategy to create a syntax from tangent points is to connect consecutive anchor points from the opposite frame. In between these tangent lines, connection lines that don't intersect the planar contour had to be defined. This allows for multiple syntax options. In this case, one of the shortest paths was selected, which was congruent to the fiber layup of the inner ring body, allowing for an almost invisible

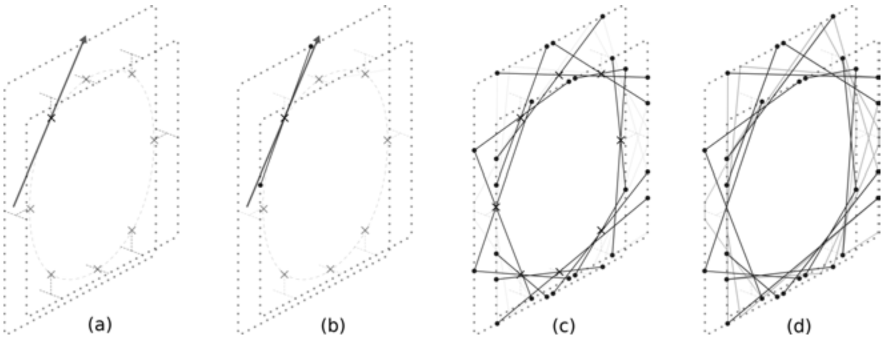

Fig. 6: Inner Ring Scaffold: Basic principles of the tangent-based approximation method for the inner ring glass fiber scaffold layer. (a) Tangent at proposed fiber interaction point, marked as X. (b) Closest anchor points of the tangent, resulting in an adjusted tangent line. (c) Adjusted tangent lines from all proposed glass fiber interaction points. (d) Adjusted tangents implemented in a continuous syntax.

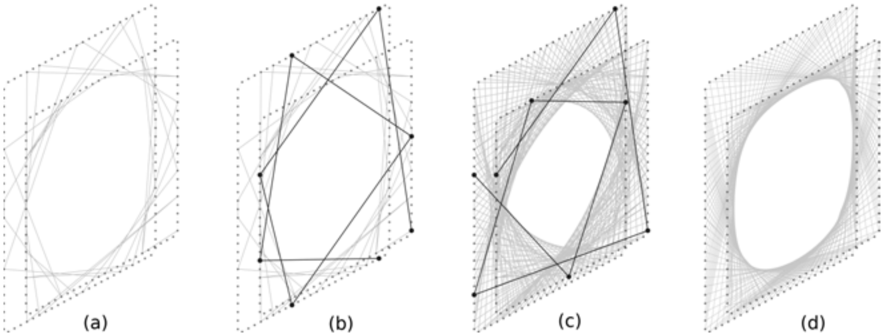

Fig. 7: Inner Ring Body: Interlaced shift syntax of the glass fiber inner ring body (a) Precursor scaffold layer, projected fiber interactions (b) Syntax for the initial winding steps (c) Syntax of the last winding steps (d) Full glass fiber layup.

scaffold layer in the final component. The design of the outline is limited to concave, circular and ellipsoidal basic shapes. A convex curve based on this design principle is not viable for the physical component, as the material behavior of the fibres and their layup in the coreless winding process do not result in positive, but only negative curvatures. However, it is conceivable that polygonised outlines can be realized instead of circle-like shapes. This would require local adjustments along the aperture in the syntax of the scaffold layer. The subsequent fiber body layer (Fig. 7) makes use of a shift value, resulting in an aperture with a smaller radius than the one in the preceding scaffold layer. The combination of a tangent-based scaffold layer and an interlaced syntax (Zechmeister et al. 2020) for the fiber body is a suitable combination for creating the largest possible axisymmetric aperture. If only the tangent-based methods were

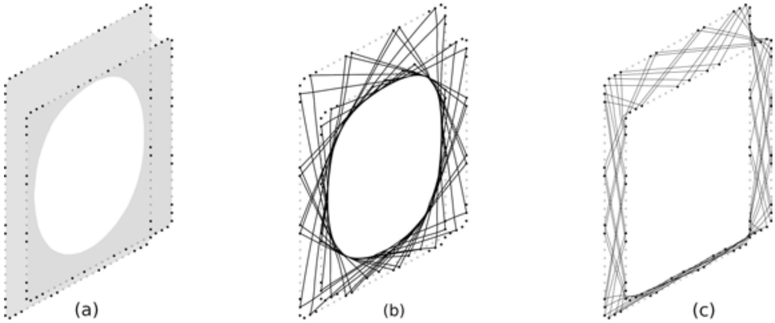

Fig. 8: Location of all connections for carbon fiber reinforcement (a) in the FE shell modell, (b) in the inner body carbon fiber reinforcement layer, (c) in the outer body reinforcement layer.

used for the scaffold layer and the fiber body, there would be a risk that some anchor points are omitted, resulting in visual gaps and irregularities in the fiber body.

The wall components were first investigated geometrically with an FE shell model (Fig. 4) to determine the efficiency and buckling behavior of the resulting inner and outer fiber bodies. Then, the connection locations were established based on the arrangement of adjacent components and the required number of anchors to be connected as analyzed in the global FE model. An additional outer fiber body was introduced, which consists of a glass fiber scaffold ensuring proper fiber interaction along the corners on the subsequently wound glass fiber body. The body uses an interlaced syntax with a low shift.

3.2 Carbon Fiber Reinforcement

Carbon fibers are considered for the load-bearing structural layer and are designed following structural guidance to carry and transfer the loads, while glass fibers are used in a more homogeneous way to provide the required geometry and fiber interaction for the component.

Both slab and wall components needed to provide a double-layered structural reinforcement to transfer the loads and create the depth of the components, based on the results of the FE beam model approach (Fig. 4). The reinforcement for the inner fiber body was structurally required and it connects structurally relevant anchor points with an interlaced shift, indicated in Fig. 9.

To complete the double-layered load-bearing structure of the wall component, an additional carbon fiber reinforcement layer was introduced to the outer body. It uses the same connections as the reinforcement layer of the inner fiber body reinforcement but spans shorter distances. As a last step, the edge reinforcement stiffens the edges of the component ensuring the load induction at the connection points.

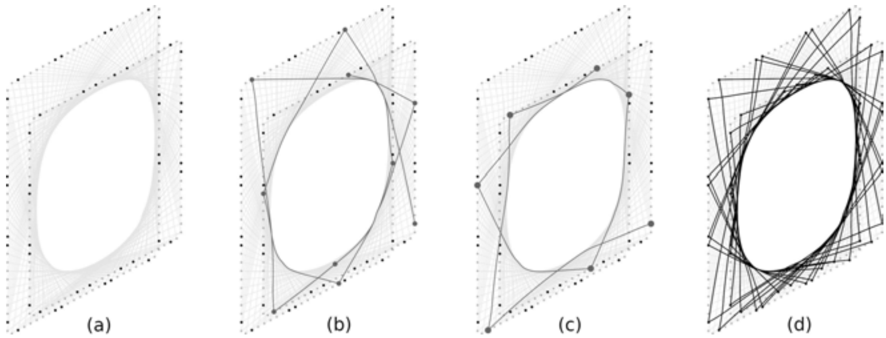

Fig. 9: Precursor layer of the fiber body, projected fiber interactions, indication of structural connections (b) Syntax for the initial winding steps, projected fiber interactions (c) Syntax of the last winding steps, projected fiber interactions (d) Full carbon fiber reinforcement layup.

The final material amount per carbon fiber bundle in this model was calibrated based on the full-scale structural testing performed for the slab component by comparing the internal forces in the fiber layup. In this way, the wall components of the first floor were designed with less fiber layers than in the ground floor. The corner reinforcements were also adjusted based on the FE model. As a result, the wall components on the first floor only weighed 47.6 kg, 22 % less than those on the ground floor (Fig. 10).

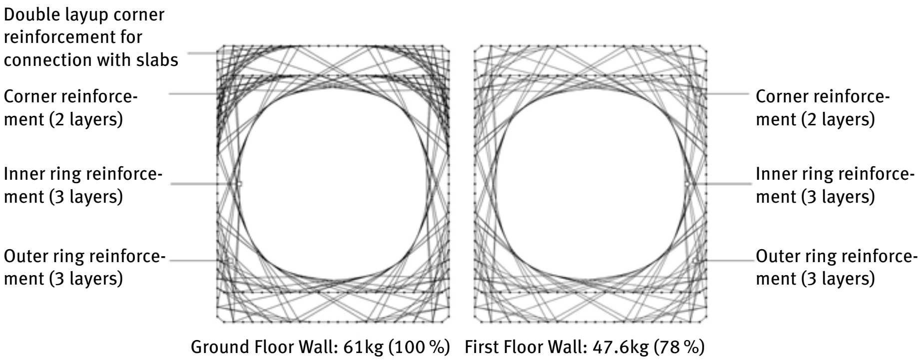

Fig. 10: Optimized carbon fiber material amount in ground and first floor wall components.

4 Results and Reflection

The co-designed modular wall system is based on a continuous knowledge transfer between architectural design, structural engineering and fabrication. The fiber layup optimization results from the structural feedback of digital and physical full-scale testing. The tangent-based approximation method facilitates the creation of a uniform aperture through approximating the circular opening. In addition to the rectangular frame geometries shown here, there's potential to realize freeform frame shapes for aperture-based geometries developed from tangent-based approximation, but this has to be further investigated. The resulting syntax should be as short as possible. Otherwise, fibers in the physical component start to bundle, causing deflections. Another aspect of the examination is the precise integration of the component in the installation. The rigidity of the frame plays an important part to ensure the correct position of the anchor points of each component. Since no frame deflection was observed, the components could be properly installed, shown in Fig. 11.

Fig. 11: Installed wall elements in the upper floor (left) and in the ground floor (right). © ICD/ITKE/IntCDC, University of Stuttgart.

The lightweight material system shown here offers geometric opportunities to reduce the amount of material used for a prototypical building and could potentially lead to a smaller ecological footprint. The LCA of the coreless winding process is currently under investigation, but early research of this and similar material systems has shown its potential in construction (Mindermann et al. 2022). Considering the speed of production – the fabrication, curing and installation of a CFW component can theoretically be achieved within 1–2 days.

5 Conclusion

This article describes the successful implementation of novel design methods of fibrous wall components. The presented methods result in the fabrication of the first coreless filament-wound wall structure built entirely of fiber-reinforced composites as part of a multi-story building. The tangent-based method enables the generation of a syntax that forms a uniform circular opening, which is challenging to accomplish using existing syntax design methods. In addition to the uniform opening, the approach takes into account the positioning of reinforcement layers based on structural feedback and the position of component connections. The presented research has the potential to be utilized in future applications in different component configurations. Further steps can include the benchmarking of fabricated components to their digital models in order to assess the accuracy of the digital design approach by 3D scanning the fabricated structure.

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