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New Reinforcement Approach for Freeform Concrete Components through Carbon Fiber 3D Printing

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Abstract

Concrete forming techniques have evolved to enhance resource efficiency and reduce dependence on traditional formwork. In contemporary architecture, freeform components have gained significance, facilitated by innovations in 3D printing (3DP), which allow for geometrically complex formworks. Despite the advancements, reinforcing geometrically complex concrete structures remains a significant challenge. This paper introduces a novel carbon fiber reinforcement method to effectively address the challenge of reinforcing geometrically complex concrete structures. The core of this approach lies in replacing traditional steel reinforcement methods with carbon fiber, implemented through digital fabrication. This research explores the application of 3DP to fabricate both carbon fiber reinforcements and precise formworks, aiming to create unprecedented structures with enhanced tensile properties. By positioning carbon fiber reinforcement on the exterior surface of concrete, where tensile stresses are most pronounced, the approach draws inspiration from conventional retrofitting processes, demonstrating enhanced structural efficiency compared to traditional methods. The proposed approach involves incorporating precisely engineered carbon fiber trajectories into pre-printed plastic formwork. After concrete curing, this method preserves carbon fiber trajectories upon formwork removal. A developed computational design strategy ensures the judicious application of carbon fiber only where structurally necessary. The research encompasses a series of experiments, including evaluations of fabrication strategies and 3-point shear-bending tests. These experiments indicate the capability of the proposed approach and the strong influence of carbon fibers on enhancing the shear and bending capacities of the elements. By integrating 3DP technologies and computational design methods, this research advances the approach for concrete reinforcement with improved material utilization in the fabrication of freeform concrete components. A fabricated demonstrator serves as a proof of concept for the practical application of this approach.

Keywords: Carbon fiber reinforcement, 3D printing, exoskeleton structures, freeform concrete, concrete elements, concrete reinforcement, digital fabrication

1. Introduction

Concrete is globally the second most consumed material after water, with an annual usage of approximately 2 billion tons[1]. The exploration of digital fabrication techniques with concrete has sparked significant interest for its ability to enable architecturally freeform structures and optimize material use. This field has witnessed considerable progress in recent years, opening new avenues for architectural design and construction efficiency [2].

1.1. Background

Digital Fabrication of Concrete (DFC) technologies predominantly focus on structural applications, ranging from individual components to entire building structures. A fundamental issue within concrete construction is the insufficiency of cement-based materials in terms of tensile strength and flexibility, necessitating the incorporation of tensile reinforcements for practical application [3, 4]. This mechanical limitation poses a substantial barrier to the advancement and maturation of DFC technologies unless strategies for embedding reinforcement within the fabrication process itself are developed [5, 6]. The traditional reinforcement methodologies applied in standard concrete construction, aimed at mitigating the material's tensile deficiencies, are largely incompatible with DFC approaches. Hence, fully exploiting the capabilities of digital design and fabrication and transformative shift in the core principles of reinforcement technology, including its planning and execution, is imperative [3].

1.2. State-of-the-art

To address the lack of tensile strength, nearly all concrete constructions incorporate reinforcement. Currently, steel is the predominant material for reinforcing concrete, though alternative options are available [4]. Using a steel bar in concrete components has the advantage of synergy between steel and concrete. However, these elements are susceptible to local buckling, poor durability, and constant confining stress after steel yielding [7]. For optimal force transfer within concrete structures, reinforcement generally adopts a configuration that mirrors the structural geometry [8]. However, this ideal conformance to complex shapes becomes difficult with steel due to its limited shapeability. Consequently, the incorporation of reinforcement in non-standard concrete structures necessitates the development of non-traditional reinforcement configurations.

Strengthening reinforced concrete structures with Fiber-Reinforced Polymers (FRP) has been studied and implemented in architecture since the early 1990s. The utilization of Carbon Fiber-Reinforced Polymer (CFRP) within the realm of FRP markedly augments the flexural reinforcement of concrete beams, evidencing an advancement in the structural integrity and efficiency of concrete components [9]. In recent years, CFRP composite structures have found an all-embracing appliance in architecture and civil engineering [7]. CFRP composites provide a high specific modulus and significant specific strength. They are matched for uses demanding superior strength and rigidity, reduced mass, and exceptional fatigue resistance. Carbon fiber, depending on the type utilized, delivers a specific strength that is roughly tenfold greater than that of aluminum and steel [10]. More specifically, CFRP has a high strength-to-weight ratio and resistance to aggressive environments with good fatigue and installation properties, as well as high formability, enabling freeform adaptation [7].

Typically, tensional reinforcements for concrete exhibit optimal performance when positioned proximally to, or directly along, the periphery of the element, as in “exoskeletal reinforcement,” where the manifestation of tensile stresses predominates [11]. However, the conventional use of steel reinforcement in such conditions can cause issues due to the material’s corrosive nature. Steel corrosion may arise if the concrete fails to inhibit the penetration of substances that induce corrosion, if the structure is inadequately designed for its operational environment, or if the environment differs from expectations or undergoes changes during the structure's lifespan [14]. In contrast, carbon fiber, with its inherent non-corrosive nature, facilitates exoskeletal concrete reinforcement. Additionally, CFRP’s superior properties, including excellent formability and lightweight characteristics, contribute to potential advantages such as reduced labor and time requirements compared to conventional materials [12].

Prior research extensively explored CFRP as a potential replacement for traditional steel rebars in concrete structures [13]. In prestressed concrete elements reinforced with CFRP bars, the effective performance hinges significantly on the bond properties between the reinforcement and the surrounding concrete. A sufficient bond strength is essential to ensure the transfer of forces between these components. The substitution of steel with CFRP alters the mechanism of load transmission between the concrete and the reinforcement. This shift occurs because CFRP materials exhibit anisotropic behavior, where their shear and transverse properties derive from the resin matrix, while their longitudinal properties stem from the fibers [15-17].

CFRP has emerged as an alternative to traditional steel reinforcement in reinforced concrete (RC) structures, offering new possibilities for construction and structural reinforcement [18]. The adoption of CFRP bars and the Near-Surface Mounted (NSM) reinforcement technique have marked significant advancements in building construction, enhancing the structural integrity and durability of concrete infrastructure [19]. CFRP's versatility extends beyond bars to mesh and grid systems, capable of adopting a variety of shapes to fit the specific cross-sectional requirements of concrete structures [20]. The HiLo project showcased the innovative application of CFRP mesh, employing a spray technique to create reinforced thin concrete shells of varying thicknesses, demonstrating the material's adaptability and performance in complex architectural forms [21].

The technology's progression in the fields of architecture and civil engineering has also introduced CFRP as a solution for the repair and retrofitting of existing structures. The material's inherent non-corrosive properties and the development of exoskeletal reinforcement techniques, such as the NSM method, offer significant benefits over traditional steel, including enhanced durability and reduced maintenance requirements. These advancements have facilitated the use of CFRP in a range of applications, from corrosion control and earthquake resistance in RC columns to the strengthening of beams and bridges, leveraging its low thermal expansion and ease of application [7].

Despite its numerous advantages, such as improved fatigue performance and reduced weight, the application of exoskeletal CFRP reinforcement in new construction remains limited, primarily due to several factors. CFRP products are generally more expensive than traditional structural materials like steel and aluminum, which can deter widespread adoption. Moreover, CFRP's conductivity of heat and electricity may limit its suitability for certain applications, necessitating careful feasibility analyses before implementation. Additionally, CFRP materials exhibit anisotropic properties and are sensitive to notches and holes, which can complicate stress analysis and require specialized design considerations, including expertise in the mechanics of composites and fracture mechanics. These challenges highlight the need for thorough cost assessments and specialized engineering expertise when considering CFRP for construction projects [22-24].

3D printing (3DP) of CFRP composites emerges as a transformative technology, enabling the cost-effective fabrication of complex structures with enhanced performance through innovative design and material utilization [25]. By leveraging principal stress line analysis, the framework bridges the gap between structural engineering and architectural design, enabling the creation of visually appealing structures optimized for both material efficiency and structural integrity [26]. Optimizing stress lines for structurally efficient designs, a framework for creating 3D spatial lattices with continuous fiber additive manufacturing enhances material efficiency and reduces weight, paving the way for innovative architectural and structural applications [27]. However, due to the increasing demand for 3D-printed strong elements and the broadening applicability of the freeform character of 3DP in composite manufacturing, new approaches to using CFRP for 3DP are also emerging. In 2016, the Composite Materials and Adaptive Structures Laboratory (CMASLab) at ETH Zurich developed a continuous CFRP 3DP method for the extrusion of high-performance CFRP materials. In collaboration with CMASLab, a precedent study developed an add-on 3DP method for the fabrication of reinforced polymer components [28, 30] that has the potential to be used as formwork for concrete. While the benefits of polymer reinforcement are well acknowledged, its widespread adoption in construction has been limited due to its primarily elastic behavior and diminished bonding strength under cyclical loading [18].

2. Approach

This research investigates a novel application of CFRP 3DP technology for the exoskeletal reinforcement of concrete structures. This approach has the potential to surpass the structural efficiency of conventional skeletal reinforcement methods and extend its utility beyond the realm of repair and retrofit applications. By enabling the fabrication of complete building components with integrated CFRP reinforcement, this technology could complement existing concrete construction in certain ways. Here, the term "exoskeletal" describes the reinforcement technique, which contrasts with traditional internal concrete reinforcement. In this method, the reinforcement is placed on the external surface of the concrete, making it visible, unlike conventional approaches.

The approach employs additive manufacturing principles, leveraging composite three-dimensional printing (3DP) technology. This process utilizes an exoskeletal framework composed of carbon fiber reinforcement integrated with 3D-printed plastic formwork. Such an approach enables the casting of concrete, facilitating the realization of freeform, tension-stable concrete building components (Fig.1). This method represents a significant advancement in the field of construction, offering a novel means of creating complex geometries with enhanced structural integrity. However, a key challenge associated with exoskeletal reinforcement is the reduced contact area between the CFRP and the concrete, leading to weaker bonding compared to traditional skeletal methods. Consequently, the effectiveness of this reinforcement strategy is highly dependent on the strength of the adhesive used to bond the CFRP to the concrete surface. Addressing this critical challenge is a central focus of this research [12].

Figure 1: Exemplary rendering image of exoskeletal carbon fiber-reinforcement

This research introduces a method that employs robotic 3DP to produce exoskeletal CFRP reinforcement for concrete. This method integrates conventional layer deposition polymer 3DP technologies for creating formworks, in combination with the add-on 3DP of CFRP materials for concrete reinforcement. The manufacturing process is outlined in the following sequential steps: 1) Initially, the design for the concrete components is generated by applying input geometry to a custom-developed algorithm, generating scripts for the 3DPg of successive polymer layers to construct a formwork. 2) The 3D-printed formwork is then repositioned using temporary 3D-printed supports to facilitate the reinforcement process. This involves the additional 3DP of CFRP onto the interior side of the formwork. 3) Subsequent to reinforcement, such multiple formwork components are assembled for the following concrete casting. Once the concrete is cured, the formwork components are removed while CFRP reinforcement remains attached to the concrete, completing the prefabrication of the architectural element. 4) As a potential scenario, these prefabricated elements can be transported to the construction site installed (Fig.2).

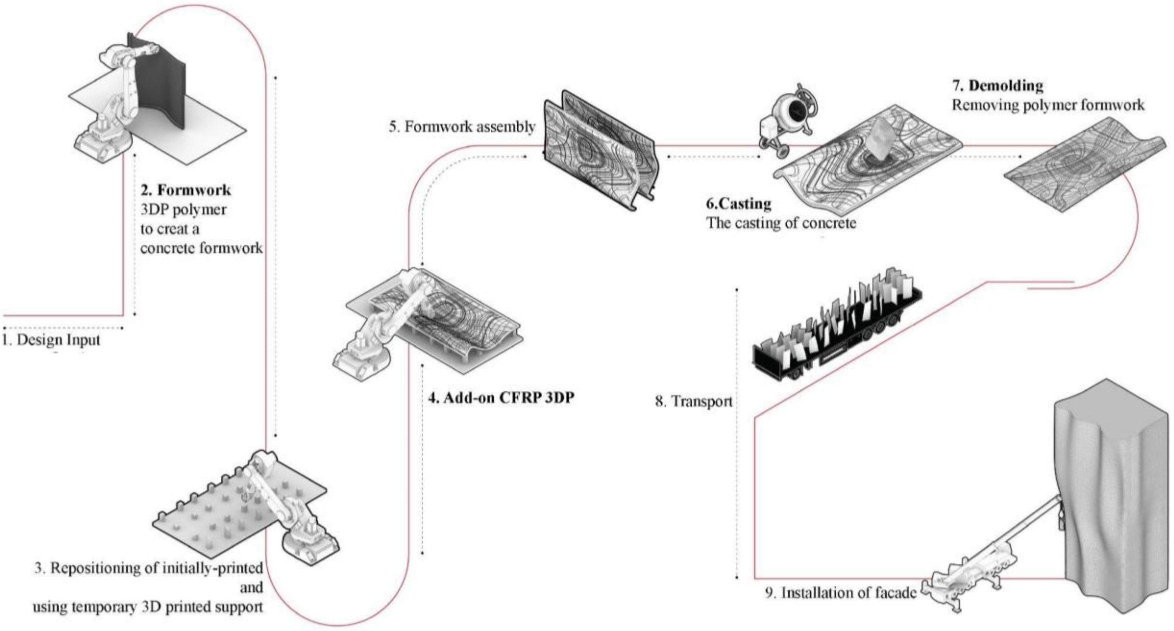

Figure 2: Fabrication steps of exoskeletal carbon fiber-reinforced concrete components.

Additionally, this research includes an exploration of designing a structurally informed CFRP reinforcement layout, which allows material reduction of CFRP to be applied only where needed.

Moreover, thin concrete structures, which are frequently chosen by architects due to their aesthetics and lightness, are the relevant geometric features of exoskeletal reinforcement, further allowing them to minimize the use of material. This new method of fabrication can efficiently reinforce the thin concrete as well as allow designers to have the freedom of designing freeform concrete building components.

3. Challenges

The development of exoskeletal reinforcement for concrete structures using CFRP confronts two principal challenges:

Bonding between CFRP and Concrete: Exoskeletal reinforcement involves affixing CFRP externally to the concrete, significantly reducing the contact area compared to traditional reinforcement methods. This reduced contact area presents a critical challenge as it may lead to weaker bonding strength, which is essential for the structural integrity of the components. The research seeks to enhance this bond through the investigation of formwork designs and strategic placement of CFRP to maximize contact surface area and improve adhesive effectiveness (Fig.3).

Figure 3: Comparison of carbon-fiber-to-concrete contact areas between exoskeletal reinforcement and conventional method

CFRP Detachment During Formwork Removal: In relation to the first challenge, a significant issue arises during the removal of formwork. The detachment of CFRP from concrete can compromise the reinforcement's effectiveness and the overall structural integrity of the built component. Thus, the study explores various formwork removal strategies that minimize the risk of CFRP detachment. These strategies include the development of non-adhesive formwork materials and mechanical methods that ensure clean separation without pulling away the embedded CFRP (Fig.4).

Figure 4: The detachment challenge of the exoskeletal CFRP reinforcement from concrete

4. Research Objectives

The proposed approach for fabricating 3D-printed exoskeletal carbon fiber-reinforced concrete structures aims to validate the feasibility of the novel fabrication strategy that integrates the materialization of plastic formwork, CFRP reinforcement, and concrete. A key objective is to identify solutions for achieving sufficient bonding between CFRP and concrete, which involves optimizing CFRP topology to broaden the contact area and developing an effective formwork removal method that avoids CFRP detachment. Additionally, the research seeks to develop a computational design method focusing on structurally informed CFRP trajectories that enables the application of this fabrication strategy to freeform shapes, thereby advancing architectural design and construction capabilities. Furthermore, the research encompasses a series of experiments, including evaluations of fabrication strategies and 3-point shear-bending tests, to demonstrate the proposed approach's capability and the significant influence of carbon fibers on enhancing the shear and bending capacities of the elements.

5. Research Method

The methodology of this research involves the testing of a prototypical design tool and the production of large-scale architectural components to validate the feasibility of a fabrication strategy that employs CFRP in freeform concrete shapes. Initial experiments focused on investigating the suitable composition of the three components—plastic formwork, CFRP reinforcement, and cast concrete evaluating the structural capacity of the exoskeletal approach and exploring CFRP topology to enhance the contact area for improved bonding. Specifically, this research develops a method that combines spatial extrusion and deposition processes of CFRP, allowing for the integration of carbon fiber reinforcement directly within concrete structures. This method facilitates a stronger physical bond between CFRP and concrete, potentially transforming the efficiency and integrity of modern construction practices.

5.1. Feasibility validation: Evaluation of structural capacity

Seven small-scale specimens were fabricated to assess the structural significance of the fibered elements using the proposed exoskeletal CFRP reinforcement technique. In the design of these specimens, considerations were made for the orientation of fibers in both vertical and horizontal directions, as well as the layering configuration, determining the number of layers stacked in the depth direction. These factors were crucial in assessing the structural effectiveness of the proposed exoskeletal CFRP reinforcement technique. Figure 5 illustrates the layer arrangement and the number of paths employed in the experimental setup for 3-point bending testing (Fig.7). To account for result variability, each specimen underwent three repetitions. The testing average results in each specimen were documented in two steps, based on the initial failure based on the primer crack in the concrete and the ultimate failure force applied by the testing machine.

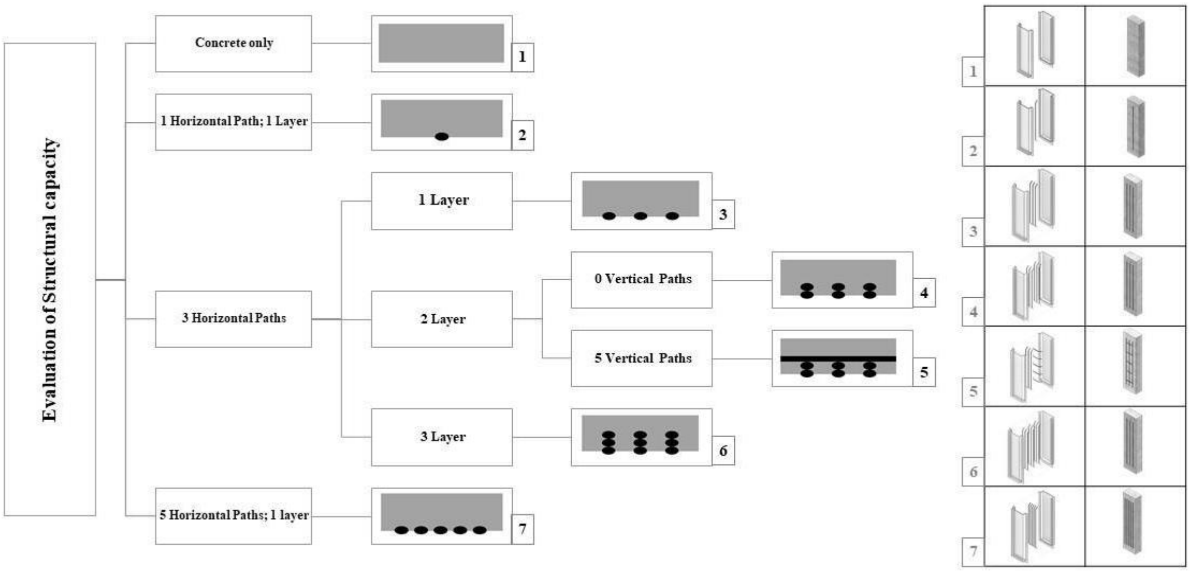

Figure 5: Parametrically manufactured samples in which the number, layers, and orientation of the CFRP

Given that bending failure, attributable to middle crack formation, was the predominant mode observed across all 21 tests, the specimens' performance can be juxtaposed with that of a concrete beam reinforced with flexural CFRP reinforcement. The reasons for failure may include compressive crushing on the top side, rupture of the rebar or carbon fibers, extension of tensile cracks, or gradual detachment of fibers from concrete due to crack extension, as observed in the present study.

In Test 1, no fiber was utilized, resulting in a brittle collapse under primer crack 10.8 MPa, equivalent to 3.62 Nm, considering the support distances in the tests, with bending occurring at the middle of the specimens. Subsequently, in Tests 2 and 3, the specimens exhibited increased ductility with the addition of fibers; however, despite the increase in fiber quantity, as depicted in Figure 9, the distances between concrete cracks and final failures decreased. Nevertheless, concrete cracking remained the primary failure mode, followed by a loss of stiffness within a capacity range similar to that of the first specimen. Tests 2, 3, and particularly Test 7 demonstrated a significant increase in capacity with the addition of fibers. Specifically, 2, 3, and 5 fibers resulted in ultimate bending capacities of 1.45, 3.0, and 6.6 Nm, respectively. Regarding the thickness of the section (2 cm), this increase in capacity exhibited an almost linear relationship.

As mentioned, another reason for primer crack failure can be the propagation of the cracks, causing the separation of the fibers from the concrete. Hence, given the high capacity of the fiber and the absence of rupture, embedding the fiber more deeply increases the cohesion between the fiber and the concrete. Tests 4 and 6, in which the number of layers increased to 2 and 3, showed that despite the positive influence of the fiber layers on increasing applied force causing the primer concrete cracks, the range of this initial failure is almost the same in all tests (Fig.7). In contrast, the effect is considerably visible on ultimate failure. Tests 4 and 6, with higher amounts of fiber along with 2 and 3 fiber layers, respectively, resist up to 22.15 and 32.2 MPa (Fig.6,7). A comparison of Tests 5 and 4, in which two layers of fiber with different layouts were used, indicates the importance of layer numbers and, accordingly, the cohesion rather than the amount of fiber, while principally the influence of vertical fibers (Test 5), in such a bending direction can be ignored. At the same time, this specimen resisted up to 8.1 Nm ultimate bending moments. Increasing the layer and number of fibers caused the specimens to maintain their stiffness after the main concrete failure.

Figure 6: Left: Fabricated samples before structural test, Right: Fabricated samples after structural test

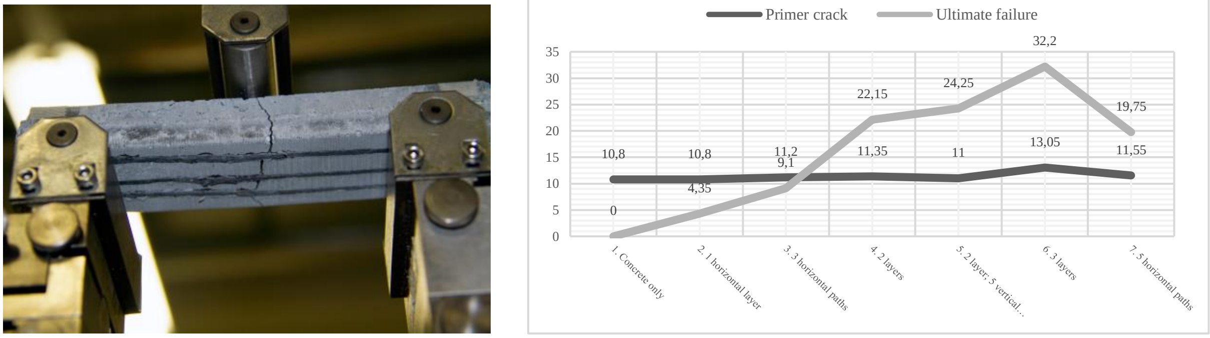

Figure 7: Left: Three-point flexural test. Right: Experimental assessment of specimens’ structural capacity.

5.2. Solutions to Challenges

In confronting the critical challenge of achieving effective bonding in the creation of large-scale building components, this research embarked on medium-scale testing. The tests uncovered pronounced issues with carbon fiber detachment from concrete during formwork removal, more severe than those encountered in smaller-scale experiments (Fig.8).

Figure 8: Carbon fiber detachment from concrete during formwork removal

To tackle these challenges, the study proposes a comprehensive strategy. Firstly, the study advocates for the optimization of carbon fiber topology to increase the contact area with concrete. This entails the addition of more fiber layers (Fig.8.a) and the introduction of anchoring mechanisms with twisted tails that embed deeply into concrete (Fig.8.b), forming a strong bond across the carbon fiber layers. To ensure the structural integrity observed in smaller-scale specimens is maintained at a larger scale, this research also suggests dividing the lengthy (Fig.8.c) carbon fiber paths to mitigate the observed detachment failures.

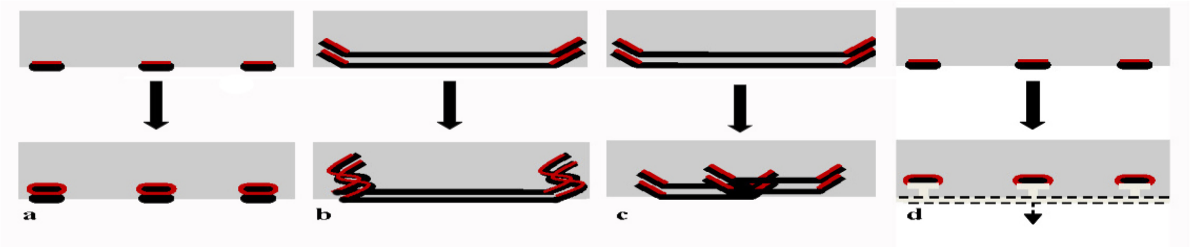

Figure 9: CFRP topology to broaden contact area: a) Layer number differentiation; b) anchoring + twisting; c) discretize excessively long trajectories d) embedding inside

Furthermore, a strategic redesign of the plastic formwork is proposed to facilitate the complete encapsulation of carbon fiber within the concrete (Fig.8.d). Among possible formwork removal methods such as heat-induced removal and chemical dissolution, the study identifies mechanical force—as enabled by a disassemblable formwork method—as the most effective strategy for preserving the carbon fiber-concrete bond. Preliminary results from comparative analyses suggest that force-based formwork removal, through the designed disassembly mechanism, offers superior prevention of carbon fiber detachment. Refinements to the carbon fiber topology also demonstrated incremental improvements in minimizing detachment issues. While complete carbon fiber embedding shows promise in eliminating detachment, it necessitates a sophisticated approach to formwork design that allows for straightforward disassembly without compromising the integrity of the embedded fibers. In conclusion, this research delineates that a solution involving short-path, double-layered carbon fiber with a twisted-anchor topology, combined with a force-based, disassemblable formwork design, emerges as the most viable strategy. This approach has been seamlessly incorporated into a computational design-to-fabrication workflow explored in this study.

5.3. Computational Design-to-fabrication Workflow

This research develops a computational design-to-fabrication workflow to facilitate the fabrication of concrete elements that are both structurally informed and material-efficient. The workflow enables them to strategically deploy material only in regions necessitated by structural demands. The workflow includes several key phases: identifying initial geometrical inputs, performing structural analyses, and formulating structurally informed topologies for both the carbon fiber reinforcement trajectories and the concrete geometry itself (Fig.10). The workflow specifically targets freeform and slender concrete elements, with a focus on geometries that do not exceed a maximum thickness of 20 mm. Through this process, various slender forms are explored for their potential as viable concrete elements, with each form undergoing rigorous testing to ensure both structural and aesthetic standards are met. The final design, a freeform table, exemplifies the capabilities of the workflow. Selected for its use of cantilever elements and a slim tabletop profile, this prototype highlights the practical application of the exoskeletal reinforcement approach in real-world scenarios. It showcases how advanced computational tools (Grasshopper, Millipede, Karamba, and Abaqus) can lead to significant improvements in the design and fabrication of architectural elements, merging aesthetic considerations with essential structural requirements. Upon application of the specified input geometry, the workflow conducts a structural analysis, generating preliminary datasets involving stress lines and corresponding stress magnitudes. The following details the specific design method developed for this research:

CFRP Layout: This method utilizes a computational analysis to map stress distributions. The design of the CFRP layout incorporates variable densities tailored to localized stress magnitudes within the structure, ensuring optimal material deployment. This strategic placement of carbon fiber reinforcement aligns directly with the areas of highest stress, significantly enhancing the structural integrity of concrete elements while maintaining material efficiency (Fig.11). In this research, the selected geometry was chosen for its use of cantilever elements and tested as a proof-of-concept on a cantilevered tabletop.

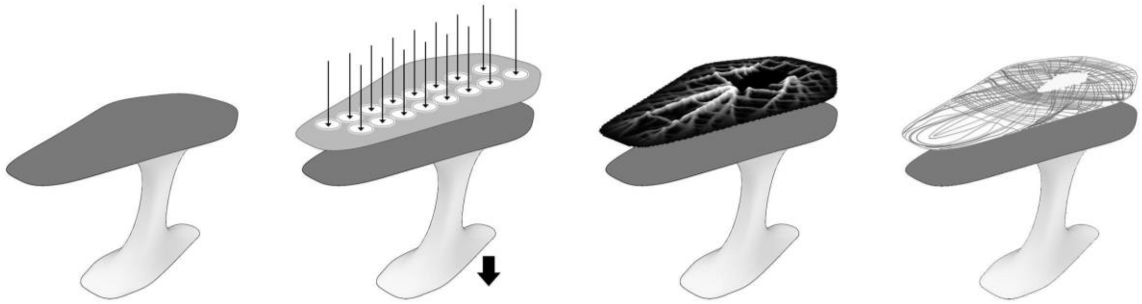

Figure 10: Computational design workflow

To emphasize the effectiveness of the reinforcement strategy, CFRP was strategically placed on the upper surface of the cantilever, where the tensile stresses are highest. This placement demonstrates the capability of CFRP to enhance the structural performance of cantilevered concrete elements by addressing critical stress areas.

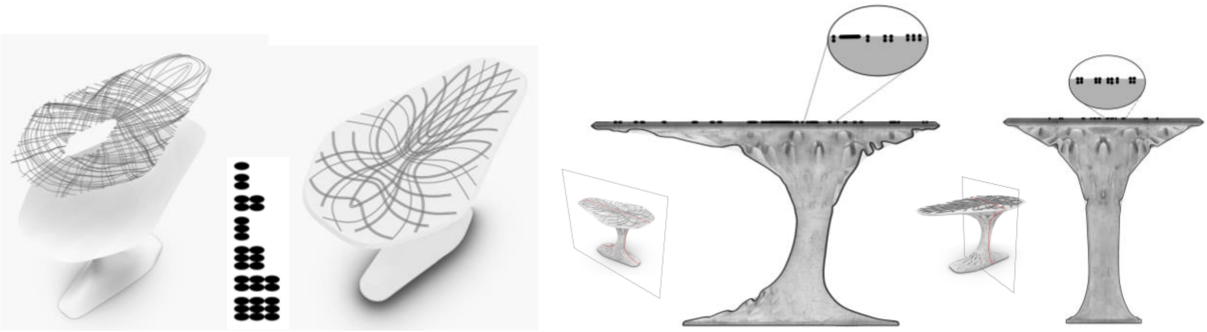

Figure 11: CFRP layout designed based on structural analysis results

Concrete Topology: Informed by the results of the structural analysis, the design process proceeds with the alteration of the concrete topology. This alteration aims for a material-efficient distribution of concrete, placing it strategically in regions experiencing high compressive loads, as identified during the analysis. The layout of the CFRP reinforcement plays a crucial role in this process. The concrete geometry adapts (deforms) to achieve topological connectivity with the CFRP layout while also enabling the implementation of variable concrete densities(Fig.12). This approach aligns with the concept of "Stay-in-Place Formwork" explored by Jipa et al. (2023) [29], where the reinforcement itself acts as a formwork, influencing the final concrete geometry.

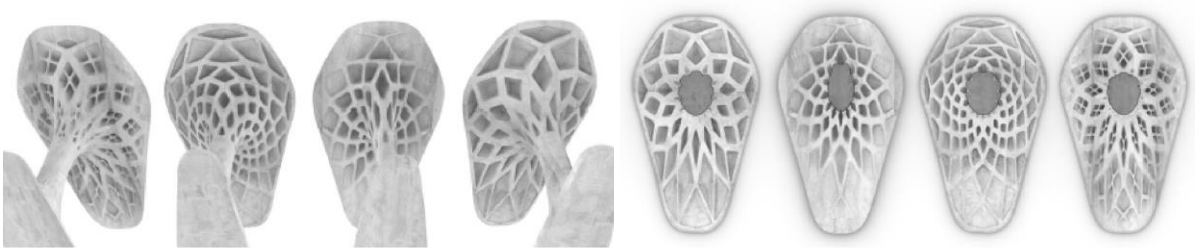

Figure 12: Variation of concrete topology

Formwork discretization: The concluding stage of the process involves discretizing the formwork geometry. This discretization translates the continuous formwork design into a format suitable for additive manufacturing using a combination of 3D printers and robotic arms. This multi-printer and multi-robot approach is particularly advantageous for fabricating intricate geometries or large-scale structures that might exceed the limitations of a single machine. A notable development in this research is a two-part formwork method. This method differentiates between regions requiring only concrete and those incorporating CFRP reinforcement (Fig.13). Concrete-only sections are discretized for efficient

3DP and assembly. These sections are designed to be demountable and reusable, promoting potential sustainability and cost-effectiveness through multiple deployments (Fig.14).

Figure 13: Regions of formwork incorporating CFRP reinforcement

Figure 14: Formwork discretization

6. Results and Outcomes

The exploration into the utilization of 3DP and CFRP for exoskeletal reinforcement of concrete structures has resulted in progress in developing a first proof-of-concept prototype, indicating a promising starting point for further research. Specific contributions are specified as follows:

Fabrication method: A novel fabrication method was developed, allowing for precise integration of CFRP reinforcement onto concrete structures. This approach leverages digital fabrication techniques, including 3DP of both the reinforcement and the formwork, facilitating the creation of geometrically complex concrete components. The method effectively enhances the tensile properties of concrete, augmenting structural integrity and enabling the realization of slender, aesthetically appealing architectural forms.

Structural performance: Experimental investigations, including a series of 3-point shear-bending tests, validated the structural efficacy of the proposed CFRP reinforcement approach. Results indicated a notable improvement in shear and bending capacity, attributed to the strategic placement of CFRP on exterior surfaces where tensile stresses predominate. This external reinforcement method not only improved structural performance but also introduced a novel aesthetic dimension to concrete components.

Computational design method: A bespoke computational design method enabled the judicious application of CFRP reinforcement. This method allows for the reinforcement patterns structurally informed, focusing CFRP application only in structurally necessary areas. This method facilitated a material-efficient design, reducing unnecessary CFRP usage while maintaining or enhancing structural performance.

Bonding challenge: Possible solutions, including the optimization of CFRP topology and the strategic redesign of formwork, were proposed to increase the contact area between CFRP and concrete and ensure the integrity of the reinforcement upon formwork removal. Notably, mechanical force, facilitated by the disassemblable formwork method, emerged as a strategy for preserving the bond during formwork removal.

Proof-of-concept prototype: The research culminated in the fabrication of a prototypical furniture element, serving as tangible proof of the feasibility and effectiveness of the proposed exoskeletal reinforcement approach. As a proof-of-concept, this prototype validated the structural and aesthetic benefits while opening the discussion toward large-scale adaptation in architecture.

The outcomes of this research contribute to the field of concrete reinforcement by introducing a novel exoskeletal CFRP reinforcement technique that offers enhanced structural performance, material efficiency, and design freedom. The integration of computational design-to-fabrication workflow opens new avenues for the use of CFRP in architectural applications, promising a future where concrete structures are not only structurally informed but also aesthetically enhanced.

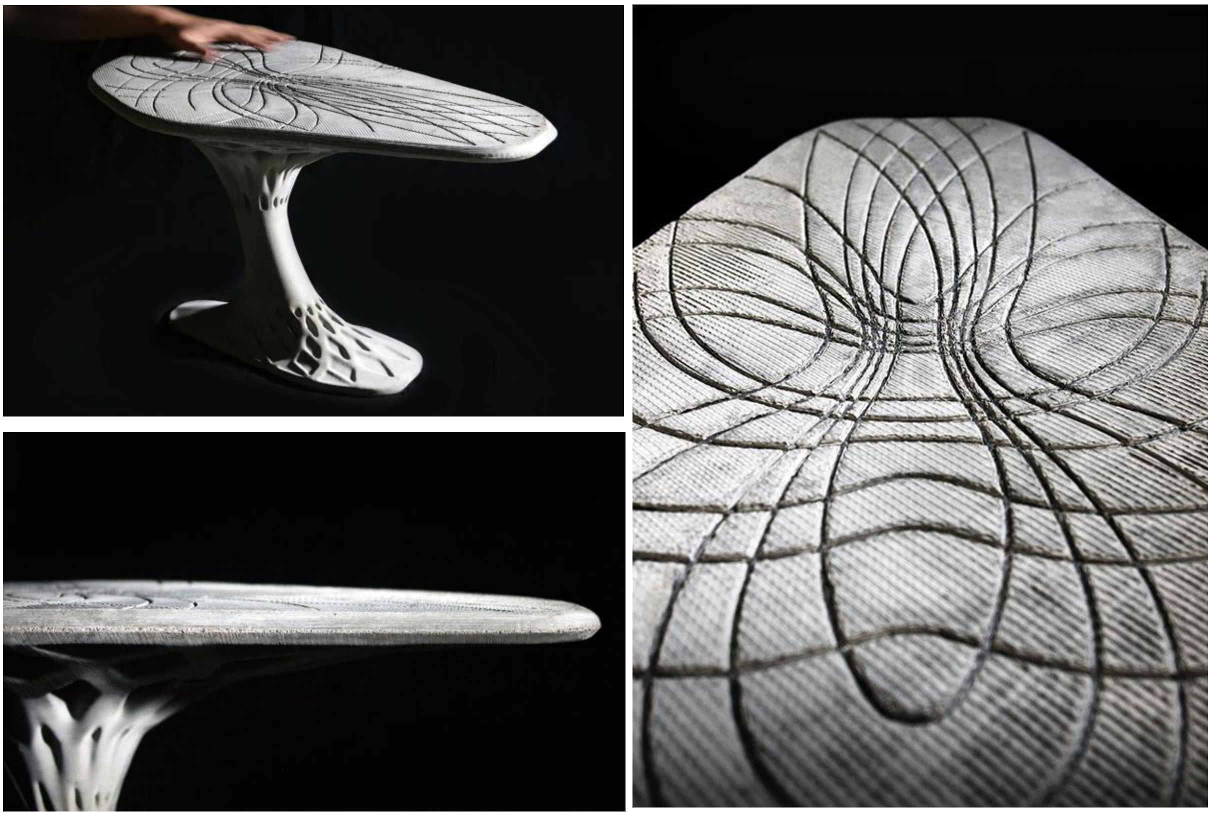

Figure14: Exoskeletally carbon fiber-reinforced concrete prototype

7. Conclusion and Outlook

This method represents a significant advancement in the field of construction, offering a novel means of creating complex geometries with enhanced structural integrity. This research has developed a method for fabricating tensionally-reinforced, freeform, thin concrete elements, with the first exploration of a combination of 3D-printed formwork and CFRP reinforcement.

The primary achievement of this research lies in successfully testing a novel manufacturing strategy that combines formwork and reinforcement for the first time. While presenting advantages and challenges, this novel approach marks a significant advancement in fabrication techniques. Despite its current limitations, the potential of this strategy warrants further exploration and refinement in future studies. The core contribution lies in the development of a novel exoskeletal carbon fiber reinforcement approach inspired by conventional concrete repair methods. This approach enables the prefabrication of architectural concrete components with efficient material usage by introducing a computational design-to-fabrication workflow that leverages structural analysis and 3DP.

Despite the promising results, several limitations of the proposed technique must be acknowledged. Firstly, while fiber reinforcement performs optimally in continuous paths, scaling up to larger demonstrators presents continuous challenges with the current tools. Secondly, the design-to-fabrication process is hindered by the absence of ready-to-use design tools, which complicates the seamless transition from conceptual design to practical implementation. Additionally, when considering large-scale applications based on component geometry and structural analysis, reinforcement will likely be needed in other areas, adding complexity to the fabrication process. Lastly, the repeated use of PLA formwork on a large scale poses a significant concern, as its durability and practicality for extensive applications remain problematic. Addressing these limitations is crucial for the further development and successful application of this novel manufacturing strategy.

However, successful implementation in real-world, large-scale architectural projects necessitates a potential optimization framework. This framework should incorporate input from a broad spectrum of experts, including architects, materials scientists, automation engineers, and structural engineers, highlighting the importance of interdisciplinary collaboration for future research endeavors. Possible outlooks include:

- Explore the possibility of a fully automated process for both 3DP and the formwork, applying the CFRP reinforcement and streamlining the manufacturing process.
- Investigate further solutions to the bonding challenge between CFRP and concrete. This might involve exploring new materials for formwork, such as water-soluble plastics.
- Examine the fire resistance properties of exposed carbon fiber reinforcement to ensure the safety of these structures.
- Develop a computational design tool capable of generating trajectories for the developed CFRP concrete reinforcement to be further structurally optimized.

While challenges remain and will likely emerge, this research lays the groundwork for a novel exoskeletal concrete reinforcement method. It demonstrates the concept's feasibility for producing complex concrete shapes by combining 3DP formwork with CFRP reinforcement, setting the stage for future advancements in the field.

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