ROBOTIC WEAVING OF CUSTOMIZABLE FRP FORMWORKS FOR LARGE-SCALE OPTIMIZED STRUCTURE

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Abstract. This research presents a novel method of robotic fabrication for customizable fiber-reinforced polymer (FRP) tubular formworks, which also function as reinforcements for large-scale structural components. This process is achieved by the spatial weaving of FRP fabric driven by a robotic arm, and calibrated with the fast-cure resin which is applied on the fabric and cures during the weaving process so the fabricated structure is self-supporting and the structure is formed in an additive manner. With this method, structural members with changing sections can be customized and fabricated rapidly with off-the-shelf materials, following a system of structural reinforcement that has been widely adopted in the construction industry and promotes new applications of construction robotics.

Keywords. Robotic fabrication; fiber reinforced polymer; structural topology optimization.

1. Introduction

Continuous studies in the structural design and topology optimization bring out the demand for the fabrication of customized structural components. Rapidly and cost-effective production of structural components have become increasingly important for the implication of optimized or formally dynamic structure systems in construction.

In the current construction projects, most of the non-standard components are fabricated via customized formworks. Time and financial cost of customizing formworks and the additional burden of transportation limit its general application. Additive manufacture, such as 3D printing, provide mass customization of non-standard components without formworks. However, as an emerging method, 3D printing faces great challenges in the process of being integrated into the workflow of the traditional construction industry. The disassociation between 3D

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printing technology and traditional construction technology makes 3D printing difficult to be applied to large-scale traditional construction projects with the current workflow.

Based on the FRP arch bridge system developed by the University of Queensland (Burnton et al. 2019), this paper proposes a fabrication method via an additive process FRP wrapping. In this arch bridge system, the prefabricated FRP tubes serve both as formwork for concrete casting, but also provide structural reinforcement. Based on the analysis of this constructed structure, this study explores the implementation of an industrial robotic system to explore the potential of FRP fabrication in terms of both geometrical freedom and flexibility for on-site fabrication, including improving the material efficiency and increasing the compatibility with the existing system. At the same time, cost and time are also important to consider.

Compared with existing construction method like 3D printing, it has the following advantages:

1. The wrapping path is planned and controlled by the robotic arm, allowing the components with diversified curvature and unconventional sections manufactured via the same process and cost.
2. Using FRP fabric role instead of FRP fiber strings effectively improves the fabrication efficiency. On the basis of the same knitting operation mode, the increase of material area also means more areas can be covered in a short time.
3. In the fabrication of large-scale components, the combination of cured FRP mold with epoxy resin offers additional reinforcement to the casted structure, and the bearing range is larger than 3D printing mode, which indicates the better mechanical performance of materials.
4. The fabricated FRP formwork is developed from an established construction system. Comparing with 3D printing, the compatibility of components fabricated by FRP is more feasible, and the assembly process will be effectively reduced.
5. FRP braided formwork will also act as a part of reinforcement after concrete casting, which avoids the waste of traditional formwork and improves the efficiency of materials.
6. The application of the industrial robot allows the possibility of on-site fabrication so as to reduce the transportation cost and avoid the transportation risk to a certain extent.

In this research, as a preliminary feasibility study, we used a Kuka KR900 robotic arm to fabricate two prototypes, Figure 1, proving the capacity of this method to additively manufacture formworks with a non-uniform cross-section and dynamic flow of profiles. With the two prototypes, we have in principle established the feasibility and flexibility of this system, which will lead to the future development of more elaborate prototypes in full-scale architecture.

2. Background

FRP has been widely used in the construction process at this stage. It is an established technology to rap and laminate FRP fiber to the surface of components for strengthening the original structure (Trung et al. 2015). Recently, concrete-filled FRP tubes (CFFTs) are becoming a common construction method shown in Figure 2 (Yu et al. 2006; Wong et al. 2008). In CFFTs, concrete-filled with the FRP section plays the role of structural reinforcement. In the load-bearing system, the concrete and FRP reinforcement compensate each other in terms of material properties. At the same time, FRP tubes also serve as a corrosion-resistant protective layer to effectively extend the life-span of concrete, and this characteristic is widely applied in bridge piers, offshore piers, etc. (Qasrawi et al. 2015; Fam and Mandal 2006).

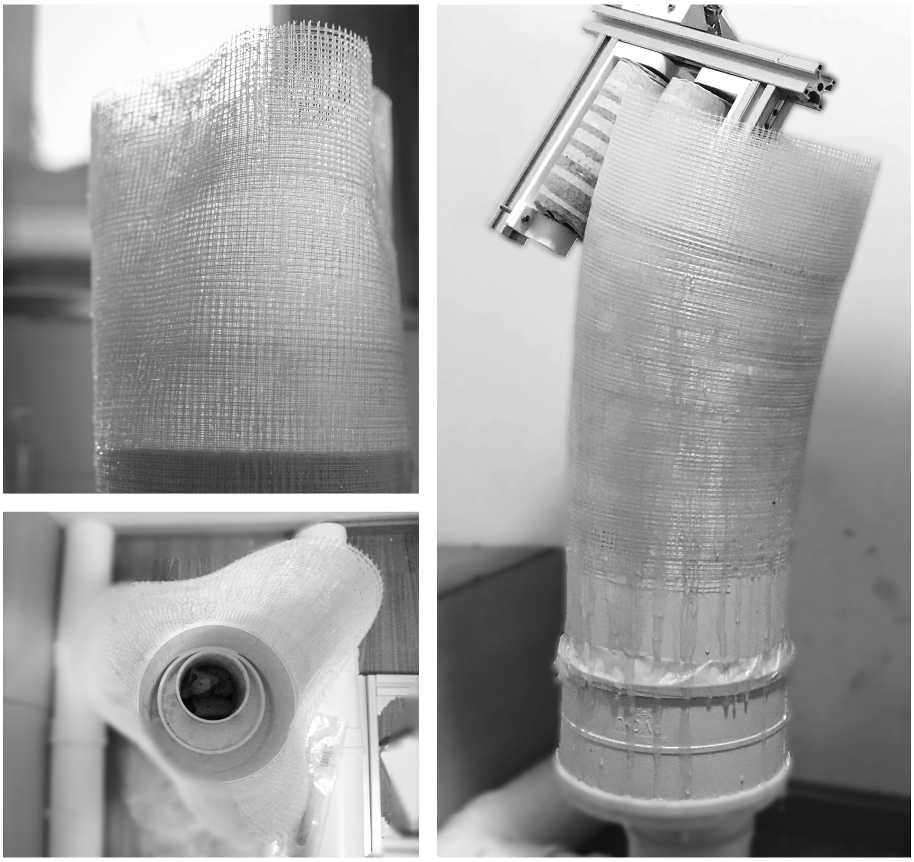

Figure 1. Left: prototype B, a tube with changing section. Right: prototype C, a tube with changing direction. .

Recent studies on structural optimization have proven that the material efficiency can be significantly improved by using topologically optimized irregular sections in replacement of the conventional sections. Within the last decade, a dynamic approach using the Finite Element Analysis (FEA) has been developed for structural optimization. This technique seeks the most efficient use of material by altering the shapes and topology and geometries of the buildings and their structural components. The optimized structures are featured with non-uniform cross-sections along the member span or height, such as the tree-like structure exhibited at 2019 IASS Form & Force Expo (Bao et al. 2019). FRP is found to be a promising material for irregular profiles because of its flexibility. However, as concluded above, fabrication of irregular structural components with conventional manufacturing techniques remains a challenge.

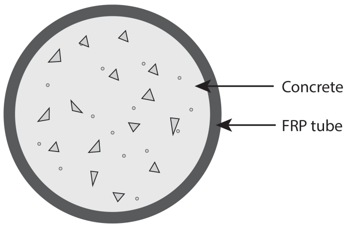

Figure 2. Cross-section of the concrete-filled FRP tubes (CFFTs).

The customized large-scale components have been intensively studied with the emerging technology of 3D contour crafting (Lloret and Shahab et al. 2015). However, in addition to the restriction of cost and speed, many of the current concrete printed components are restricted in terms of structure strength due to the difficulty in reinforcement and joinery. In term of compatibility with current construction process, fabricating formwork for concrete casting has significant advantage over direct 3D printing. Brian Peters from Kent State University has investigated a method of using patented fused deposition modelling (FDM) for fabricating formwork (Peters 2014). His research exposed the challenging aspect of expanding from small scale to large structure scale formwork due to hydrostatic pressure exerted by the concrete. Submillimetre Formwork project (Burger and Lloret et al. 2020) from ETH Zurich provide another alternative of using typical FDM robotic printing to fabricate formwork while simultaneously casting into it. However, the formwork in those cased serves as a means to the end for casting concrete, raising the challenge of material efficiency and integration.

Following the concept of additive fabrication and the precedence in FRP weaving, this paper presents a novel fabrication method for the mold/mandrel-free FRP tubular sections, providing a feasible method for on-site fabrication of customizable formwork for optimized structure members with non-uniform cross-sections.

3. Experiment workflows design

This experiment mainly focused on challenging two unconventional FRP forms: variable cross-section and variable mandrel, which are the two major types of non-standard form. The outcomes are able to propose the possible construction solution strategy of the BESO structural analysis result.

3.1. ROBOTIC SYSTEM DESIGN

3.1.1. End effector / working radius

In this experiment, a KUKA KR900 robot was deployed and it's working area can meet the size requirement of the final outcomes (300mm * 300mm * 800mm), Figure 3. An end-effector was developed to guide the fabric waving and to carry the GFRP roll. In this preparation phase, the size of the end-effector is designed to carry a 50m long, 100mm wide fiber fabric roll, which is enough to extrude an 500mm tall column with an average diameter of 200mm. The current end-effector requires a 120mm clearance on the inner side of the tube to operate, which restricts the minimum diameter of the column to be 120mm.

At the left side of the end-effector, a pair of passive sponge rollers were set to rotating along the outer side for positioning and ensuring the accuracy of sections, and one supporting aluminum profile is designed to hold the fiber fabric in a passive way. By adjusting the gap between two sponge rollers can tighten the fabric and provide pressure on the newly-weaved fabric, so it is fully appended to the previous layers and socked with the resin.

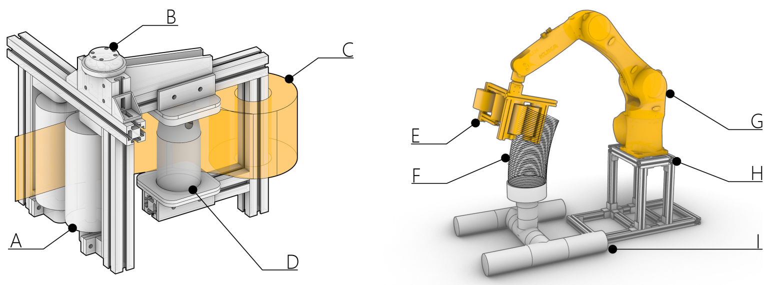

Figure 3. The end-effector and working environment. (A) Passive roller. (B) Head of the end-effector, connected to KUKA. (C) FRP roll. (D) Epoxy resin dispenser. (E) End-effector. (F) Path for wrapping FRP. (G) KUKA KU6 R900. (H) Base for robotic arm. (I) PVC platform.

In the middle of the tool, a bottle fixed to the aluminum profiles was set to hold the resin and gluing the fiber belt by three small holes automatically. So, when the fiber belt slide forward to the sponge rollers, it will pass through the resin storage bottle and will be gradually tainted by resin. The big hole on the top of the bottle was designed to refill the resin quickly.

3.1.2. Endless axis

The working path of the weaving end-effector demands a dedicated designed path. It has to be ensured that there is no collision with the surrounding work environment, the existing FRP tubular, and the KUKA robot itself. Besides, the working process of weaving FRP seems like wrapping up the fracture patient, which means the trail of the fiber belt should be a continuous trail rotating around the mandrel. Therefore, the A6 axis of the robot arm was set to the endless mode so as to break the normal angle limitation between +175 and -175 degrees. Figure 4 demonstrates the FRP weaving process.

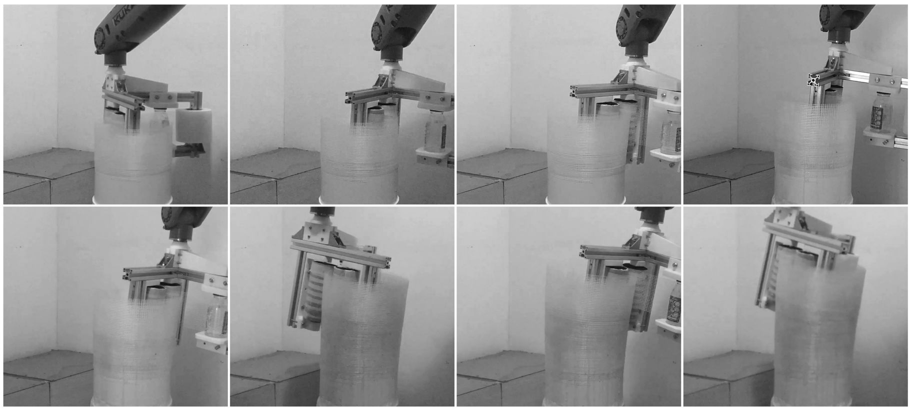

Figure 4. The sequential process of the robotic weaving method.

3.2. CRAFT TECHNIQUES

3.2.1. Calibration

The experiment is a continuous process, where the fiber fabric was rotating along the mandrel from beginning to end. Even a little error or fault will lead to the accumulation of errors, Figure 5. Normally, the deviations come from two aspects: the end-effector of the robotic arm and the platform in the working environment. The first one is able to be calculated and calibrated by the preset program in the robotic arm, just following the guide in the controller one by one manually. However, the latter one is hardly noticeable in the working space, where the floor may not precisely horizontal and the platform may not parallel to the KUKA robot. All the deviation is inconspicuous that is hard to be noticed by eyes- maybe just several degrees. Thus, an efficient way to fix the problem is remapping the coordination of the physical world to the digital model. By detecting three points along the outside of the PVC pipe, a series of coordination will be input in the Rhino so as to define a circle with a plane. When exporting the path-planning program for the KUKA robot, the deviation that comes from the ground slopes will be calculated. Therefore, before the experiment, the calibration of the end-effector is significant to the accuracy of the final outcomes. In order to test the accuracy of the system setting and the tool calibration, a circle drawing program was applied to test.

3.2.2. Platform

The fabrication platform was made of PVC pipes with two diameters. The 110mm one was used for the platform support, and the 200mm one was used for connecting with the FRP as the foundation of the tubular. The PVC pipes and the relevant accessories such as the tee-junction are easy to achieve from the construction material market and convenient to assemble according to the design paper. The structural performance of the PVC pipes is strong and it is able to be replaced effortlessly after one of the experiments is finished. However, the lightweight of the PVC pipes is not firm enough to provide an immovable foundation, so the interior of the pipes was full filled with cobblestone.

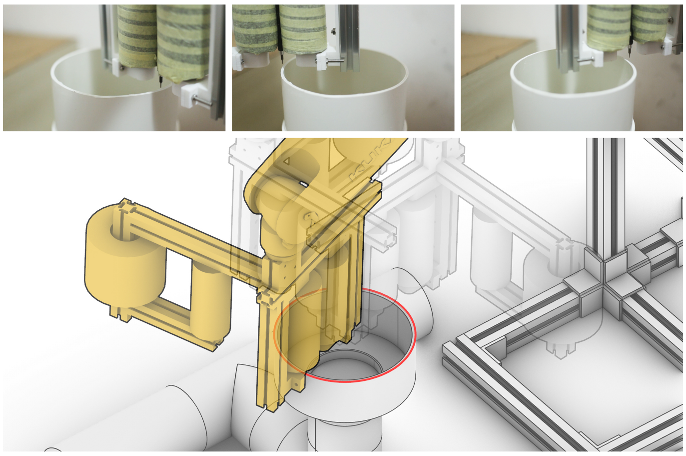

Figure 5. calibration and detection.

The PVC pipes only serve as a platform for the beginning part, which is similar to the brim layer in the normal 3d printing and it will be removed from the FRP after weaving. The cured resin is hard and strong, so the fret saw was used to split these two parts.

3.3. MATERIAL PROPERTIES

Commercial bidirectional glass fiber fabric with 100mm width and 150 g/m2 was used for this study. The fabric has a plain-woven structure with a count of 3 threads/cm in both warp and weft directions. The mix ratio used in this experiment was 100: 2 by weight for the epoxy resin and hardener. The prototype was fabricated in the indoor environment with a temperature of 15 degrees, a 100g resin was used in each mix, and the pot life (working time) was about 20 mins before the viscosity of the mix is too large to be applied by brush. When fabricating a cylindroid form, all the fiber fabric is spread on the mold neatly. However, the fiber fabric is not an elastic material. So, when wrapping a non-standard form, the gaps between layers are obvious, resulting in a deviation from the final outcomes, Figure 6.

Besides, the number of fabric layers at each cross-section of the tube is critical for the success of the fabrication process. When the layers are not enough, the stiffness of the tube would be too small to hold the top layers during weaving, while if too many layers of fiber are used, the fabrication time would be prolonged and the material efficiency is reduced. In this application, a series of trials have been conducted to find the balance between the construction speed and section stiffness. A result of 15 layers of GFRP fabric in each standard section was found to provide adequate support for the upper layers.

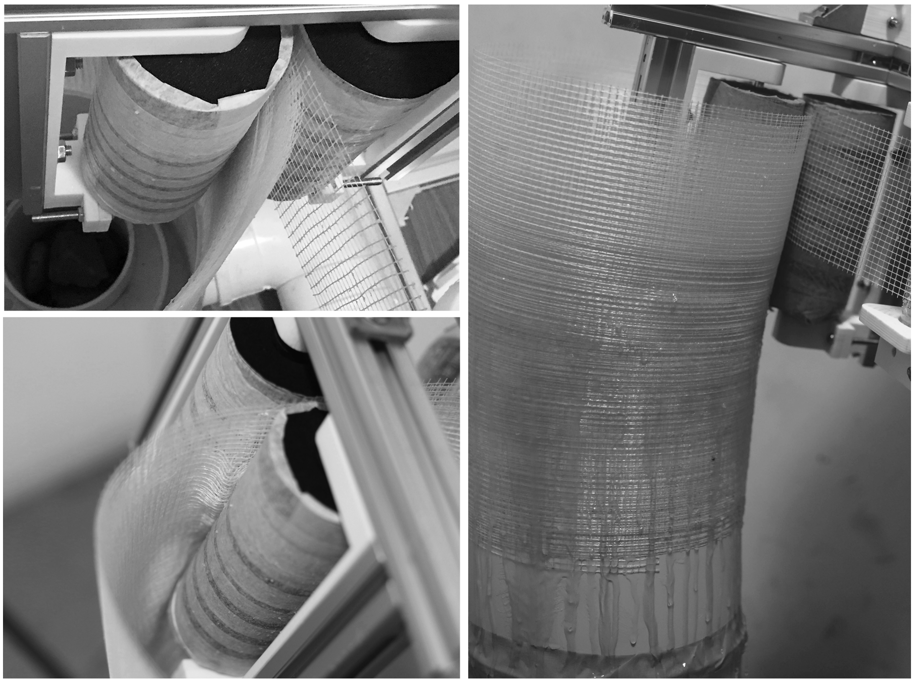

Figure 6. Left top: Gaps between layers. Left bottom: Deviation accumulated. Right: The uneven finished surface .

3.4. EXPERIMENT SUMMARY

A series of tests have been carried out with two non-standard FRP form components that were fabricated to explore an appropriate combination of resin curing time, speed of movement, and the number of layers. Based on the experiments, several limitations are concluded for FRP robotic fabrication:

1. The resin cure time will influence the efficiency of the experiment. In the normal room temperature of approx. 25 degrees, the new wrapped fabric should be cured for approximately 45mins. However, the temperature is changing in a day, so the cure time varies from 30mins - 60mins. Especially in the variable cross-section experiment, the experiment will stop waiting for the resin cure at three significant transformation points. Therefore, how to decrease-curing time of resin should be explored in the future.
2. The size of the end-effector and the height of the fiber fabric affect the variation of the variable cross-section FRP. It is as same as the concept of "DPI" which is commonly used to define the detail level of the screen. A smaller roller on the

inner side of the tubular will generate more details. So, the height of the fiber fabric is similar to the "height of layer" in 3d printing.

3. The ideal finishing surface should be smooth and shiny with an evenly applied resin. However, the uncured resin will flow down due to gravity, resulting in a rough outside surface of FRP, Figure 6.
4. The feasible FRP form for fabrication is limited because as a non-framework system, the stability during the weaving process is based on the weaved and cured FRP part.

4. Application in the fabrication of customizable structure component

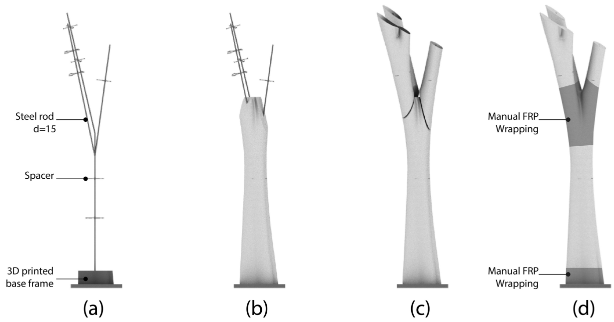

Figure 7. Assembly sequence: (a) inner structure, (b) weaving of the base, (c) assemble the branches, and (d) reinforcement with manual wrapping at the joint and base.

The robotic fabrication for customizable FRP formworks technology integrated with the BESO method has the potential to serve the building industry due to its capability of producing large-scale customizable structural components with high performance and low cost. Recently, the general solutions to fabricate the complicated surface in the practical architectural field are casting, planarization or 3d printing, etc. However, both of the methods mentioned above have their challenges. The planarization is often used in the double-curved curtain wall, but it is not self-supported because normally the panels are fixed to the metal support system. Although the 3d printing technologies have developed rapidly in recent years -many materials were employed in the research prototypes including concrete, PETG, or clay - the structural performance is still limited. So, the spatial FRP waving system proposed in this paper has more potential in the practical application, comparing with the other method.

Inspired by the tree branch shape columns in Sagrada Familia Basilica, the Bi-directional Evolutionary Structural Optimization (BESO) method offers the opportunities to mimic the morphology of biological structural system with a direct and rational connection between form and material (Mattheck 1998). Figure 7 shows the possible construction method of the tree branch system optimized by BESO algorithm.

5. Conclusion

This paper explores an innovative additive manufacturing technology to construct customizable FRP formworks for building structure, by integrating the advanced robotic fabrication and the dynamic FRP wrapping technique. In this research, two preliminary prototypes were fabricated and verified, proving the fabrication feasibility. This method will be extremely beneficial for the construction of topological optimized structures.

As a representative scenario, the experiment also demonstrates how the new digital design and robotic fabrication process collaborated together could effectively increase the cost, time, and material efficiency, while allowing more flexibility in the fabrication of the highly optimized non-standard structure. The proposed method is developed based on an established construction system and has the potential benefit of incorporating it into the existing construction process with minimum adaptation effort.

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