KNITTED COMPOSITES TOWER

Design Research for Knitted Fabric Reinforced Composites Based on Advanced Knitting Technology

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Abstract. Faced with growing urbanization demands of developing countries and global shortages of construction materials, this research looks for an innovative light-weight high-performance material system for architectural applications. The knitted composites tower is a 7.2-meter, 260-kilogram and self-supported prototype that uses 2mm thick knitted fabric reinforced composites. The result is lightweight and strong. It demonstrates the design potentials of knitted fabric reinforced composites. This article takes knitted composites tower as an example to illustrate a design method for knitted fabric reinforced composites. The design method covers three aspects of structural form selection, structure arrangement, and microscopic configuration. At last, the complete fabrication and construction process will be discussed with a full-scale physical prototype.

Keywords. Knitting; Composites; Architectural Design.

1. Introduction

Faced with growing urbanization demands of developing countries and global shortages of construction materials, this research looks for an innovative light-weight high-performance material system for architectural applications. We test knitted fabric reinforced composites material using advanced knitting technology and set up related design methods.

Flat knitting is highly potential for creating light-weight and high-performance structures. Flat knitting allows complex properties and details to be integrated into one single piece of fabric using a minimum amount of materials, it also allows flexible material manipulations in response to complex structural and environmental conditions. Moreover, flat knitting allows high-speed and low-cost mass customization, which is crucial for architectural production. And when combined with polymers, textiles can become structural.

Numerous researches have been carried out to explore the design potentials of knitting. Advanced flat knitting machines and related computer-aided design systems have enabled designers to custom architectural products with flexible definitions of reinforcement, porosity, density, yarn combinations, joints, etc.

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(Thomsen et al. 2016, Sabin 2013, Ahlquist 2015). Knitted textiles have been integrated with pneumatic or bending-active elements to become light-weight hybrid structures (Thomsen et al. 2015, La Magna et al. 2018, Ahlquist et al. 2013, Ahlquist et al. 2017), or with functional elements for lighting, heating, sensing, monitoring, etc. (Dias 2015). Automatic knitting information generation methods (Wu et al. 2019, Popescu et al. 2017, Narayanan et al. 2018, Liu et al. 2019) have enabled designers to customize 3D fabrics with complex geometry.

2. Design Method

This article takes a knitted composites tower as an example and proposes a design method for knitted fabric reinforced composites to give full play to the advantages of the material. The design method proposed by this article covers three aspects, including structural form selection, structural arrangement, and microscopic configuration. Structural form selection searches for an appropriate structural form for the material system. Structural arrangement establishes distribution patterns of structural elements, such as fabric patches, reinforcements, holes, and connections. Microscopic configuration generates distribution patterns of knitting stitches and stitches' internal structures.

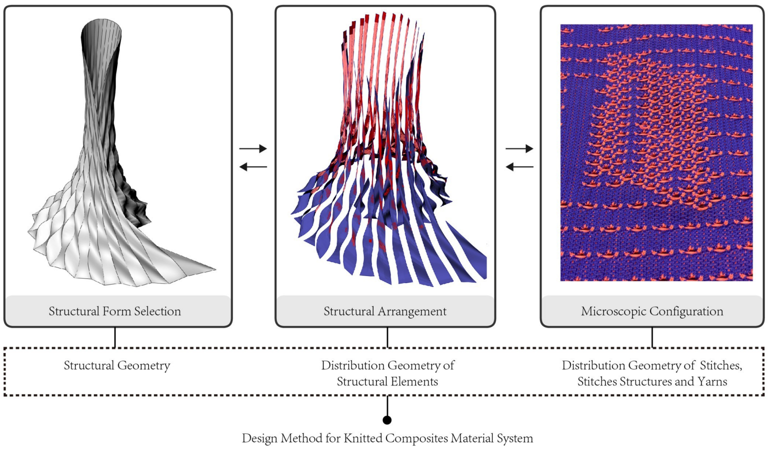

Figure 1. The design method covers three aspects of structural form selection, structure arrangement, and microscopic configuration.

2.1. STRUCTURAL FORM SELECTION

In structural form selection, major challenges are, first, knitted composites tower belongs to fabric-formed shells, so its structural form should allow uncured fabrics to get balanced under weight loads, second, knitted composites material is only 2-3mm thick, but is required to support a 7-meter tower. In response to those challenges, knitted composites tower uses a spiral anticlastic surface as the basic geometry since anticlastic surfaces are very common equilibrium forms in membrane structures. Furthermore, creases are introduced to help increase structural effective thickness as well as stability.

The final surface of the tower is controlled by a series of horizontal spirals and 36 vertical crease curves. The wavy surface is created by lofting the crease curves in pairs. Geometry variables of the structural surface include spirals' diameter, creases' depth and creases' quantity. To determine the parameters of those variables, we used finite element analysis plug-in Karamba3D (Preisinger 2013) to compare the performance of structural forms with different surface curvature, diameters and crease modes. Elastic energy, max displacement and max Von Mises stress are major indicators for evaluation. Elastic energy reflects overall stability, max displacement and max Von Mises stress illustrate local stability. And the smaller the values are, the more stable is the structure. The analysis result shows that better structural stability can be achieved when diameters of horizontal spirals are in a linear relationship, or the diameter of top or bottom becomes smaller. Moreover, increased crease depth enhances local stability, smoother upper parts of creases enhance overall stability. At last, it should be noted that, though structural performance is the most important criteria for choosing a good structural form for knitted composites, the final result is not necessarily of the best structural performance, instead, it is a balanced result, which has a relatively good structural performance while balancing all other criteria, such as fabrication time, spatial perception and aesthetic preferences.

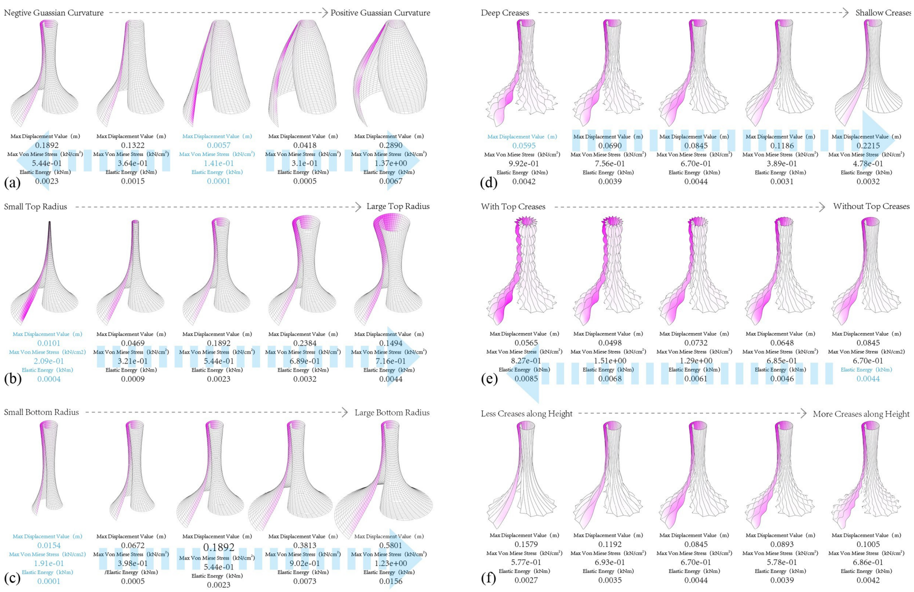

Figure 2. The structure is more stable when diameters of horizontal spirals are in a linear relationship (a), or the top (b) or the bottom(c) is small. Increased crease depth reduces local displacement (d), smoother upper parts of creases increase overall stability (e), quantity of creases doesn't show clear influence over structural performance.

2.2. STRUCTURAL ARRANGEMENT

Structural arrangement determines distribution patterns of fabric patches, connections, reinforcements and porosity. Major challenges in structural arrangement include, how to divide the structural surface into fabric patches that are beneficial to structural performance, knitting process as well as construction convenience, how to appropriately extract stress concentrated area or material redundant area from the structural surface to add reinforcements or porosity.

In the tower project, the seams of fabric patches follow longitude crease curves. In this manner, we can fully take advantage of automatic knitting machines, and make fabric patches as large as possible, eliminating unnecessary connections. Besides, this division pattern enables the geometry of each fabric to be easily controlled by inserting curved steel plates along its two edges. Moreover, arranging seams in a vertical direction is beneficial to enhance structural stability against weight load, since seams have a greater stiffness than other parts of the fabric. Finally, the structural surface of the tower is divided into 35 pieces of fabric. The quantity makes sure that the width of each fabric is within the width limitation of a knitting bed, yet still making the most use of it.

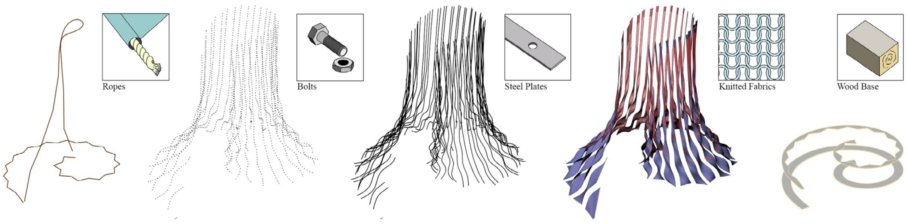

Figure 3. Major structural elements of the knitted composites tower.

The distribution patterns of holes and reinforcement are informed by stress conditions within the structural surface. We used Millipede (Michalatos and Kaijima 2014) plug-in and its built-in topology optimization algorithm. The algorithm reduces material mass to a prescribed percentage and shows the stressful area in a thickness map after optimization. Following this thickness diagram, we can easily extract less stressful area from the structural surface and adjust local porosity according to thickness value. With increased porosity, local polymer materials are reduced in the related area. Moreover, we used a deformation analysis model generated by Karamba3D (Preisinger 2013) to inform the distribution of reinforcement. At places that tend to show obvious deformation, such as free edges, holes are removed and an extra rope is added to increase local thickness and fiber content.

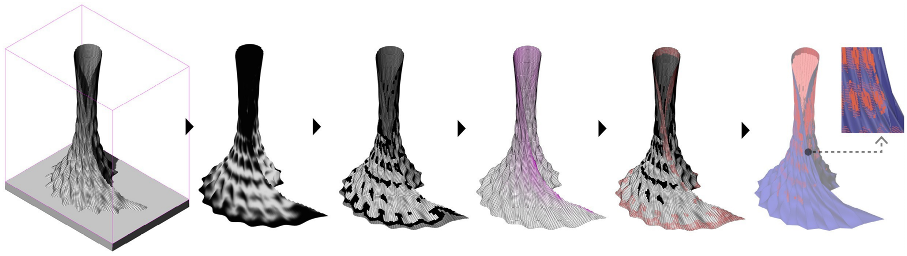

Figure 4. Distribution of porosity over the structure is informed by stress distribution within the structure.

2.3. MICROSCOPIC CONFIGURATION

Microscopic configuration discusses distribution patterns of stitches over fabrics, stitches' internal structures and choices of yarns. Challenges in designing the microscopic configuration of knitted composites structures lie in three aspects. First, how to generate a stitch distribution pattern that not only responds to the 3D geometry, pattern and connection details of a fabric but also obeys knitting logic, since a stitch is a fabrication unit of a fabric? Second, how to determine the combination of stitch structures? Third, how to evaluate yarn choices?

To generate a stitch distribution pattern, we developed a program in Grasshopper (Rutten 2019). Each fabric model with bespoke shape, pattern and connection details can be automatically translated into a stitch model. The inputs of the program include a fabric surface, models of patterns and details and stitch size parameters. The output of the program is a multi-color bitmap containing stitch distribution data and stitch structure data. The bitmap can be directly used for production.

The generation process of stitch information includes flattening, defining patterns and details, defining stitch structures, rasterization, knittability optimization, translation into machine actions and non-uniform scale. Compared with computing stitch distribution directly on 3D surfaces, flattening simplifies calculations, which is beneficial for large fabrics with millions of stitches. After flattening, an automatic rotation is made to make sure the maximum width of a flattened surface is within the width limitation of a knitting machine. Then, patterns and details are represented as lines and dots, they are created either by unfolding models from 3D or by drawing directly on the flattened surface. Colors are also added to define different stitch structures. To get the exact location of each stitch over the surface, rasterization is carried out. During rasterization, each stitch is represented as a rectangle, whose width and height are identical to the input stitch size parameter. To make the stitch distribution pattern knittable, the program optimizes the layout of stitches to make sure that each knitting row can be smoothly connected with its next row, and all stitches can be linked by a continuous zigzag curve, which represents the knitting path. Finally, the program translates stitch structures into symbols of machine actions and uses a non-uniform scale to transform stitch drawings into a knitting diagram. In the knitting diagram, each pixel represents a stitch, each color represents a series of machine actions. In knitted composites tower, each fabric is translated into a 18-color bitmap. The bitmaps can be directly imported to Stoll's M1 plus Software and production can begin soon after defining machine actions for each color and adding a cast-on template.

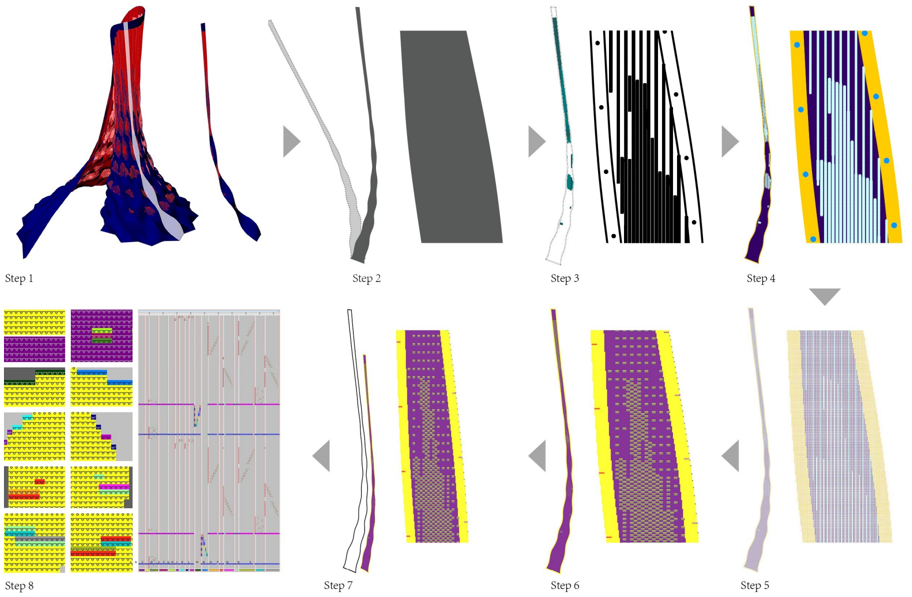

Figure 5. Generation steps of stitch information include flattening(step 2), defining patterns and details(step 3), defining stitch structures(step 4), rasterization and knittability optimization(step 5), translation into machine actions(step 6) and non-uniform scale(step 7).

The combination of stitch structures is determined by designers and technicians together according to required effect, details, knitting constraints and performance. A double-sided tuck structure is chosen as the major stitch structure for the tower project. This type of stitch structure can achieve the effect of red and blue on each fabric side, it also allows arbitrary connection status of a fabric's two sides in one knitting row. The two sides can be either interlocked or separated at random places, and when they are separated, a hollow sleeve is created, allowing for inserting steel plates or reinforcing ropes. In addition, we also introduced lace structure to form lace holes, and increase, decrease, cast-on, cast-off stitches to shape irregular contours of fabrics, openings and bolt holes.

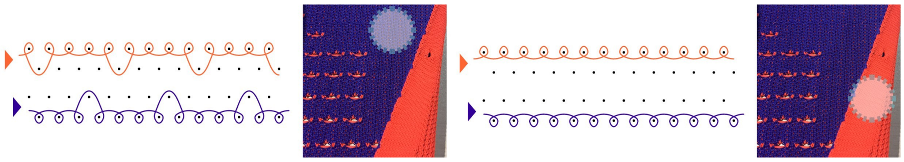

Figure 6. Major stitch structures for the knitted composites tower.

To find an appropriate type of yarn, we compared engineering yarns and common yarns. Engineering yarns, such as yarns made of carbon fiber, glass fiber, aramid fiber, are of high modulus, but very few of them are flexible enough for knitting, especially when required stitch structures are complicated. Moreover, engineering yarns often have limited choices of thickness and color. Compared with engineering yarns, polyester yarns offer a wider range of colors and thickness, but tests have to be made to prove their structural capability for this project. Our tests follow Chinese national standards GBT1447-2005 for testing the tensile performance of fiber-reinforced polymer composites. Given material mechanical properties and estimated weight, we evaluated the deformation status of the structure and concluded that polyester yarns were sufficient for the tower project. The choice of polyester yarn is also affected by the issue that knitted fabrics may become darker when saturated with polymers. Such a problem can be solved by using yarns with fluorescent colors since they can maintain brightness when immersed in polymers. However, such color cannot be found in engineering yarns.

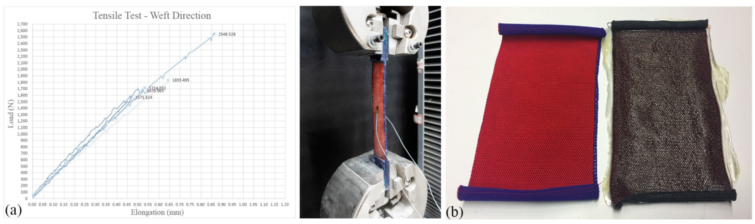

Figure 7. Tensile tests for knitted composites(a), and the color of knitted fabrics(c) get dark when saturated with polymers.

3. Fabrication and Assembly

In the tower project, we used four Stoll CMS 502HP automatic knitting machines to fabricate 35 pieces of fabric. There are over 200,000 knitting rows in total and the knitting time is more than 137 hours excluding time spent on tests and errors. For each piece of fabric, knitting time varies from 50 minutes to 5 hours, depending on the size of the fabric and the complexity of the craft. Wooden base, wooden top panel and steel plates are cut by CNC machines. Grooves are left on wooden panels for positioning steel plates, holes are drilled on steel plates for connection.

The 3D geometry of the fabric is controlled by steel plates, therefore positioning the steel plates becomes the key aspect of positioning the tower. One centimeter wide steel plates were first inserted into the sleeves on fabrics' edges. Both steel plates and edge sleeves have pre-set bolt holes, so that neighboring fabrics can be connected by fastening bolts through adjacent steel plates and fabric sleeves. After connecting neighboring fabrics, upper ends of steel plates are tied to top panels using 3mm steel cables with predefined lengths. Then, top panels are raised to the top of scaffolds and the whole structure is suspended from top panels. After fixing the bottom of steel plates and fabrics to the grooves on base panels, the structure is ready for adding polymers.

We used EL2 laminate epoxy from Easy Composites and took one kilogram as an operation unit. Since the interior of the tower is not wide enough to put a scaffold, epoxy is mainly used on the outside of the tower, except for areas within reach of students and workers. The application of polymer materials takes two times for the tower. However, we find that multiple applications of epoxy results in glue stains and uneven gloss on the surface. In response to this issue, we used matte varnish on the surface to reduce unwanted luster.

4. Result and Discussions

The final knitted composites tower is 7.2 meters high, 260 kilograms and is self-supported. The effective structure is achieved by using a small amount of material compared with conventional structures. This light-weight and high-performance tower pushes the limit of knitted composites and demonstrates the design potential of the material.

Figure 8. Perspective(a) and interior detail(b) of the tower.

The major limitation of this research lies in the issue of wrinkles. Wrinkles are caused by the following reasons: 1. Steel plates are slender and easy to deform even though its two ends are fixed. Extra position points in the middle should be added, however, during construction, positioning points for the middle are not sufficient and accurate, so the actual shape of steel plates are not identical as the design model. 2. During generating knitting information, a uniform stitch size parameter input is used. However, stitch sizes of different stitch structures are different, such as the stitch size of lace holes is larger than that of plain stitches. It causes the calculated number of stitches to exceed actual demands, and redundant stitches result in wrinkles. 3. The equilibrium form of a fabric-formed structure is also affected by internal force distribution. To further control the realization of structural form, the design process should consider a method to accurately control the distribution of force within the structure. 4. The structure surface is simply suspended rather than properly tensioned, so the fabric don't have enough inherent stress as well as stiffness. As a result, the weight of epoxy can easily lead to deformations of fabric, causing more wrinkles.

In the future, the design method for knitted composites will be further improved. We look forward to integrating form-finding and tension force control with current methods. Future improvements on stitch placement generation will focus on robust computation methods to generate stitch information directly from large-scale 3D surfaces, to allow multiple stitch size inputs and alignment with principal force fields.

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