Prototyping Method for Complex-Shaped Textile Composite Panels

Developing a digitally controlled reconfigurable mold

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While textile composites offer a wide range of formal flexibilities, a primary concern is the cost and time of creating custom mold surfaces which are typically produced through subtractive digital fabrication techniques. Alternative methods such as adjustable molds are used in high-end sail-making, and architectural researchers have examined reconfigurable molds, fiber sandwich fabrication methods, and mold-free fiber reinforced polymer (FRP) fabrication processes. In this paper, we discuss the development of a digitally controlled mold system for complex-shaped textile composite panels, aiming to reduce the need for custom milled molds. Experimental research started with producing composite samples from computer-numerically-controlled (CNC) milled foam molds. Subsequently, a digitally controlled deformable mold prototype was developed which incorporates a digital interface through which the architect's surface geometry is entered, analyzed, and transferred. The digital geometry directly controls the position of vertical actuators which adjusts the mold surface. Results of this ongoing project outline a digital process for fabricating textile composite panels, and help to define key parameters of the adjustable mold system including material properties, mechanical controls of the mold surface, paneling considerations, and digital interface.

Keywords: *textile composites, reconfigurable mold, deformable mold, fiber reinforced polymer, digital fabrication, Arduino*

INTRODUCTION

Textile composite materials have been implemented more recently in a few high profile complex-shaped architectural projects such as the San Francisco Museum of Modern Art expansion (2015), Chanel Pavilion (2008), One Ocean Pavilion in South Korea (2012). There are a number of general barriers adopting this material for buildings including fire performance, and the technical complexity of engineering the fibers and matrices into components. While textile composites are of interest to architects because of its formal flexibility and lightweight characteristics, from a constructability standpoint they pose challenges of high cost and time to produce custom shaped molds (Kreysler 2016; Bell et al. 2014). With parametric design and digital fabrication having made it possible to produce non-standard and differentiated products more economically, a number of researchers examined alternate production scenarios and methods for architectural composite applications. Corazza et al. (2014) investigated geometric behavior of fiber composite sandwich material for exterior building applications to eliminate mold production, and Bell et al. (2014) researched digitally reconfigurable surfaces for non-repetitive geometries focusing on composite applications. Kreysler (2016) explains the industry challenges and potential of fiber reinforced polymer (FRP) applications in high-rise buildings. Blonder and Grobman (2015) discuss a mold free FRP form finding and fabrication approach. In most cases these approaches are still in research phases and new manufacturing solutions are strongly desirable to address the cost concern of many industries. Reconfigurable molds are not just of interest to the building industry. The same problem is present in other industries such as automotive, marine, aerospace, transportation and energy industry. All these industries are facing the cost issue to manufacture highly non-standard complex shapes with high accuracy. Therefore, the need to research facade panels' materials and manufacturing processes is still current and a vital topic to architecture and many other industries.

BACKGROUND

The authors are interested in the potential of textile composites as a new building envelope material for its formal and performative possibilities and have focused on developing alternative methods to replace the costly mold making process with a digitally controlled adjustable mold system. Precedents exist in the high-end sail making industry, 3DL (Pearson 2010), and in research, Bell et al. (2014) mention TailorCrete and Schipper (2015) who has developed flexible molds. In this paper, we describe an approach that integrates commonly used software Rhino3D, Grasshopper, Firefly, Autodesk Alias, off-the-shelf Arduino microcontroller, actuators, and textile composite material to develop a customized digital fabrication approach. A number of precedents are discussed in more detail.

Renzo Piano (Schipper 2015) carried out comprehensive research and development on flexible mold techniques for manufacturing architectural elements. He developed a process to produce double-curved fiber-reinforced plastic elements. The mold could also be used for the construction of reinforced concrete shells and consisted of a grid of plungers supporting a flexible surface on top. The plungers would shape 3D curved elements of plastic structures, and Piano constructed a number of experimental pavilions using this technique. Nakajima (1960) explored the idea of creating reconstructed shapes of small diameter pins and wires bundled together. He was looking for the ability to stamp the thin sheets of metal into a double-curved shapes. Two ways were used to form surface contours: (1) numerical point-point control using a push rod and (2) incrementally changing the die shape using a triangular-shaped pusher that swept back and forth across the backside of the tool surface. Rao and Dhande (2002) explored flexible surface tooling based on the concept of discrete approximation to a continuous mold or die surface. Closely spaced multiple rigid surface tool elements (i.e., indentors) which adjust to the desired contour shape. The positioning of each indentor is controlled manually or digitally. A deformable elastomeric sheet is placed over the indentors to reduce the tool surface unevenness. Finite element analysis is carried out to analyze the deformation of the rubber-like membrane in multiple contacts. Pronk et al. (2009) studied different molding techniques to make 3D surfaces with prefabricated elements. Their prototype contains a tensioned flexible layer (1200 mm × 1800 mm) which is manipulated with manually set actuators. The actuators are only positioned at the edges and consist of upper and lower array arrangement. Thus, the accuracy of the edges is essential for the edge transitions of the panels. This mold can produce polyester and composite panels combining vacuum injection molding. Lee and Kim (2012) discuss mass customization of double-curved metal facade panels using a new hybrid sheet metal processing technique for the Dongdaemun Design Park designed by Zaha Hadid. The project involved 45,000 non-standard shaped facade panels among which approximately 22,000 panels were double curved. Three methods were tested to find an optimal metal forming technique. The process was based on computer-controlled hydraulic multipoint forming processes to achieve smooth stretching and pressing of fixed sheet metal into double-curved surfaces. The precedents discussed above are a small sample of various approaches which attempted to create molds of various scales, materials, and curvatures. Key parameters of the mold processes identified include actuation mechanisms, resolution of actuation points, mold surface material and properties to relate to the design surface geometry, and final product material properties and limitations.

METHODS

The various stages of developing a prototype for textile composites paneling and production strategy are explained.

Textile Composites Experiments

Textile composites are fiber reinforced composite materials that combine fiber with a matrix resin. The project team studied textile composite fabrication using various fiber fabric including glass fiber, carbon fiber, and Kevlar. The composite samples were produced using one sided CNC milled surface molds which were modeled in the Rhino3D software to create various complex-shaped surfaces. The physical samples were formed using a hand layup process during which reinforcing fiber layers and epoxy resin were placed on the mold, and then cured at room temperature, or vacuum bagged to compress the resin and fiber. These experiments were expanded in a course with students working with four-unit clustered panels to study formal qualities of textiles and continuity between panels (Figure 1). As the students were using an open mold process, some of the more intricate concave shapes required to apply sufficient pressure to the setback or sloped areas to achieve the mold form. The edges of the adjacent panels were cut to form thin sheets. The samples illustrated that if the panels edge returns would need separate layers to create fluid edge corners.

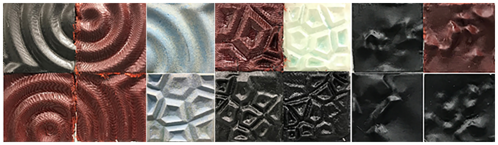

Figure 1
Textile Composite Samples.

Architectural Surface Geometry

Textile composites can be easily formed into free forms but the fabrication process defines a number of parameters (e.g., panel edge slopes, mold surface curvature limitations, panel size, etc.) that impact the surface geometry. We adopted a panelization strategy of sandwich panels which bonds a foam core between thin sheets of composite material to increase shear stiffness. A hypothetical curved building surface was considered and divided it into quadrilateral panels using geodesic curves (Figure 2). The panel edge conditions require continuity to adjacent panels and to its internal area. Using Rhino3D curvature analysis such as Gaussian and Min radius, developable surface areas and minimal curvature areas are identified to determine candidate panels that can be fabricated within the mold shape limitations (Figure 3). Figure 3 illustrates how low curvature panels, higher and complex curvature panels are sorted based on the curvature analysis.

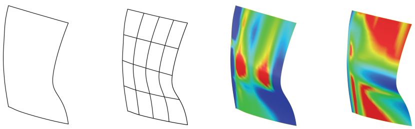

Figure 2
Surface Geometry Subdivision and Curvature analysis.

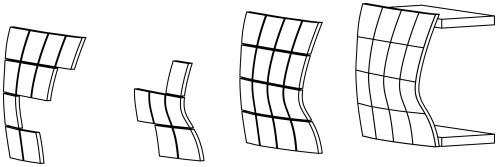

Figure 3
Building Surface Panelization and Classification based on Analysis.

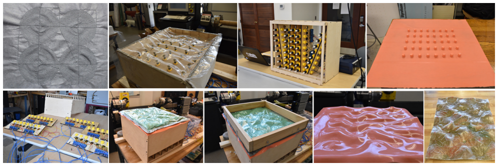

Figure 4
Prototype Development Process.

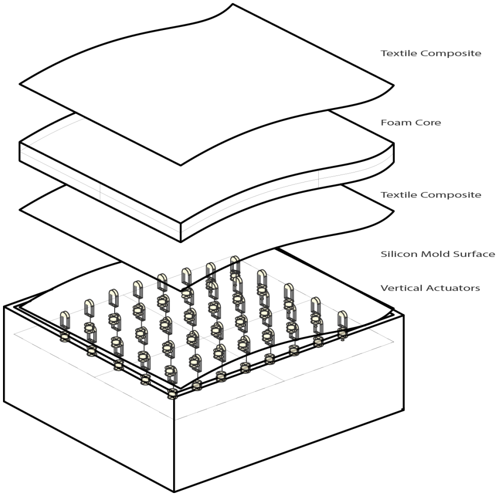

Figure 5
Prototype Diagram

Adjustable Mold Prototype Development

Based on the panelization strategy explained above, an adjustable mold system was designed and developed. Two digitally driven adjustable surface techniques were explored to substitute the standard disposable CNC milled foam surfaces (Figure 4). The first technique was based on shape memory alloy (Nickel Titanium or nitinol wire) which shrinks or expands in response to temperature changes incurred through electric current. Various nitinol patterns were embroidered utilizing tailored fiber placement technology to study surface deformations. Figure 4 shows an example of a circular pattern. This approach was unsuccessful because it produced only small amounts of displacement and difficult to relate required surface deformations to specific embroidered patterns.

The subsequent approach (Figure 5) adopted a mechanically driven solution using vertical actuators (low cost car door lock DC motors) controlled through an Arduino microcontroller with shift registers and relay array. The surface resolution was set up as a 5x8 grid of actuators with a maximum stepping height of 1" for each actuator. Figure 5 illustrates the horizontal surface, actuator array, and frame. The array is covered with a silicone membrane that holds the resin or epoxy matrix and provides the mold surface for the fiber fabric. A vacuum bag can be applied on top of the mold to compress matrix resin and fabric. The actuators have enough load capacity for supporting the forming activities. The interface control is achieved through the Rhino 3D/Grasshopper Firefly plugin which translates the panel surface geometry into required heights of the actuators.

The mold is used to form two composite surfaces which are used both as formwork and final surface, injecting expandable foam that becomes the core of the final sandwich panel.

RESULTS AND DISCUSSION

The team produced a series of fiberglass FRP samples to measure how close the physical samples' geometry were to the digital surface models. The physical samples were scanned using a Structure Sensor 3D Scanner and compared against the original Rhino3D surface geometry using Autodesk Alias mesh-to-mesh deviation mapping (Figure 6).

Composites Surface Geometry Results

We tested 12 samples (three samples per four different configurations). The four categories included an undulating double curved surface, a single curved undulating surface, and concave and convex hexagonal dome surfaces. As illustrated in Figure 6, the double curvature surface highlights deviations of surfaces around the apexes. The deviations are due to the silicon mold surface deformations occurring around the actuator heads, and placement errors of the actuators which slightly deviate from the original grid. The single curved sample undulations conform better than the double curved sample but still deviate from the original surface geometry for the same reasons.

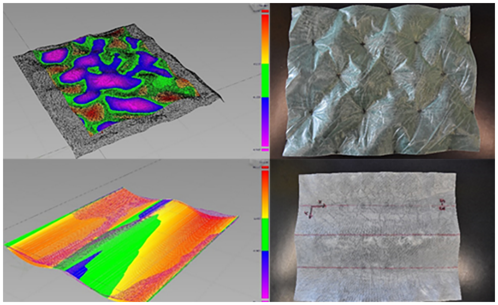

Figure 6
Composite Sample Surface Deviation Results.

The samples also illustrated continuity issues along surface edges of complex curved surfaces. It was observed that edge surfaces deviated from the original surface geometry because the mold surface is fixed horizontally at the mold frame. The mold is also limited in controlling edge surface tangents because the actuators only fully extend or retract when actuated without intermediate position control.

The results offered important insights into the characteristics of the mold surface material and also relevant issues to be considered for further design and development.

Mold Prototype Considerations

A number of issues appeared during experimentation with the prototype, including mechanical, electrical, and physical mold issues as follows:

- The actuator displacement control is limited to full extension or retraction making intermediate control difficult. The team developed a workaround by disengaging actuators that did not require full extension or retraction so that they would follow the position imposed by the mold surface profile.
- Actuators overheated and broke during lengthy vacuum bagging processes which typically lasted for about 13 hours.
- The single sided open mold required an upper counter pressure component for concave shapes. The actuator retracted locations need additional vertical loads to conform to the concave mold surfaces.
- The injection of the expandable foam for the sandwich panel requires a separate mold and pressurized injection process to consistently distribute the foam core between the two composite sheets.

CONCLUSION

We discussed the development of a digitally controlled adjustable mold surface prototype for complex-shaped architectural textile composites. This research contributes to the growing knowledge body of textile composites for architectural applications, specifically the issues of geometry control and adjustable, reconfigurable mold surfaces and processes which offer potential to improve the feasibility of complex-shaped textile composite applications. The prototyping endeavors helped to establish key parameters of an adjustable mold system, including the geometric properties of mold surface material, design and analysis interface, sandwich core material injection and formation process, and electric circuits and actuator placement and control issues.

Future work will focus on characterizing alternative mold surfaces and corresponding mechanical and digital controls such as geometric algorithms that offer better material feedback about specific geometries to the designer. We will begin analyzing structural performances of textile composite material properties and construction detailing of the panelized system joints to address waterproofing, load transfer and construction assembly issues.

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