Digitally-driven Fabrication of Fiber-reinforced Composite Panels for Complex Shaped Envelopes

DANIEL CHUNG
Drexel University

KIHONG KU
Philadelphia University

Composite materials have been explored in architecture for their high performance characteristics that allow customization of functional properties of lightness, strength, stiffness and fracture toughness. Particularly, engineering advancements and better understanding of fiber composites have resulted in growing applications for architectural structures and envelopes. As most new developments in material fabrication start outside the realm of architecture such as in automobile and aeronautical industries, there is need to advance knowledge in architectural design to take advantage of new fabrication technologies. The authors introduce results of new digitally driven fabrication methods for fiber-reinforced composite sandwich panels for complex shaped buildings. This presentation discussed the material properties, manufacturing methods and fabrication techniques needed to develop a proof of concept system using off-the-shelf production technology that ultimately can be packaged into a mobile containerized facility for on-site panel production. The researchers conducted experiments focusing on developing a digitally controlled deformable mold to create composite relief structures for highly customized geometrical façade components. Research findings of production materials, fabrication methods and assembly techniques, are discussed to offer insights into novel opportunities for architectural composite panel fabrication and commercialization.

1. INTRODUCTION

The demand for large scale free form shapes in architecture and the push for high performance building materials and systems has brought evident changes in the building industry. The completion of the Bilbao Guggenheim Museum in 1997 marked an important accomplishment in the implementation of digital design and manufacturing tools (Kolarevik, 2003). With the availability and precision of 3D modelling tools and direct control of fabrication via CNC equipment, free form architectural projects have become more affordable. Such digital tools have broad implications on production and design processes involving changes in the roles and arrangement to generate and control design (Ku et al., 2008). In case of complex shaped envelopes, designers have focused on rationalizing surface geometries to optimize and maximize standardized components reducing the high cost of fabricating and installing non-standard components (Glymph et al., 2004; Whitehead, 2003).

Alternatively, designers and researchers have turned to technological advancements in materials and fabrication techniques used in the automobile, shipping, and aerospace industries for innovation. Addressing the inefficiencies of constructing continuously changing curved forms with traditional structural systems (Yun and Schodek, 2003) and layered systems for enclosure (Lynn, 2010); there have been attempts to adapt fiber reinforced polymer materials. Instead of using conventional systems composed of primary load-bearing structural members, secondary structure and connecting systems that support layers of insulation, waterproofing, and exterior finishes, some designers are exploring new methods of applying laminated composites with integrated structure.

There are a number of challenges to adopting composites such as the lack of standards for assessing the structural performance under various loading conditions and understanding long term impacts of aging and durability (Fernandez, 2006). While there are a number of architectural composites manufacturers (e.g., Kreysler & Associates, CA, USA; Trespa International BV, Netherlands; Acell, Milan, Italy; PCT, Dubai, UAE), cost is typically higher than common building materials[1]. Composites are functionally customizable but for the majority of building applications such levels of customization are unnecessary and costly. Thus it is necessary to understand how to best take advantage of the customizable characteristics of composites with economically feasible means of production. Future complex shaped envelope production will benefit from a better understanding of state-of-the-art fabrication methods. This is gained through a literature review of current panel fabrication methods and experimental design research involving hands-on prototyping of composites panels. In this article, investigations of the impact of digitally driven composites production processes are described to contribute to the growing knowledge base of architectural composites.

2. RESEARCH GOAL AND APPROACH

The ultimate goal of this research is to develop a framework for a digitally driven mobile containerized factory of architectural composites for complex shaped building cladding systems. The objective for this paper is to document the initial explorations of developing a composites panelling and production strategy involving a deformable mold prototype. This project targets the production of cost effective composites cladding systems which can efficiently enclose space while also producing complex envelope geometries (Chudley and Roger, 2010).

The background section explains the geometric rationalization of complex shaped building envelopes and relevant composite production approaches. The next section discusses composites panelization strategies and the following section elaborates on the prototype development process. The conclusion discusses the findings and future steps.

3. BACKGROUND

3.1. GEOMETRIC RATIONALIZATION OF FREE FORM SURFACES

Large scale free form building shapes have direct cost impacts. Design of complex shaped buildings often involves rationalization of project geometry to increase the number of identical components, flat units, and consequently reduce the number of unique curved panels.

For construction, curved surfaces are generally more difficult to produce than flat ones and ruled surfaces are easier to produce than complex parametric surfaces (e.g., NURBS curves or B-splines). Ruled surfaces can be generated by the rotation or translation of straight lines and include developable surfaces (e.g., cylinders, cones) which can be flattened without cutting or stretching the original surface and non-developable surfaces (e.g., hyperboloids, spheres, and hyperbolic paraboloids) which require cutting and stretching to be transformed into planar sheets (Schodek et al., 2005).

In general, these strategies for creating large complex shapes via panelization can be grouped into three categories. First and least expensive for the panel fabrication is dividing the complex shape into a series of facets, often triangles or polygons that allow the panels to be flat. Second is the geometric division of the complex shape into flat and single curve panels. Sheet metal panels can be readily roll formed into single curves without the use of expensive forms. Third is the use of multi-curved panels. (Schodek et al., 2005). These tend to be the most expensive and have often required the most amount of time to produce. Generally, the larger the rate of change and the greater the number of curves the more difficult it becomes to fabricate the panel.

Design rationalization strategies include simplification of NURBS geometries to arc-based geometries (Whitehead, 2003), modification of design geometry to conform to the physical constraints of planar quadrilateral panels (Glymph et al., 2003), or adjustment of the inter-panel distances between adjacent panels within positional and normal continuity (Eigensatz et al., 2010).

As such it is important to understand the significance of geometry in design for manufacturing. Digital design tools offer guidance in analysing manufacturability by supporting Gaussian and mean curvature interpretations to analyse isotropic materials such as metals, or normal curvature evaluation of non-isotropic materials such as wood and reinforced plastic materials (Schodek et al., 2005).

3.2. RELEVANT COMPOSITES APPROACHES

Composites offer opportunities to produce curved components observed in products from the automobile, shipbuilding and aerospace industries[1] such as the fuselage of Boeing airplanes (Lynn, 2010). Pearson (2010) describes the process of producing high performance race boats sails which involves lamination of PET film, thermoplastic resin, and structural yarn (custom patterned with carbon, aramid, UHMWP fibers), and another layer of film. The process relies on an adjustable 3D male mold which matches the custom sail curvature imported from a 3D CAD/CAE file. Composites can offer greater formal freedom than metals and deformed sheet materials to designers because they can be configured into highly complex geometries through molding processes.

Fiber reinforced plastics can be made from a variety of fibers (e.g., polyehtylene, polypropylene, aramid (AFRP), glass (GRRP), carbon (CRFR), etc.) (Fernandez, 2006). Combined with flexible formal possibilities, composites can be functionally customized to serve a variety of architectural applications.

4. COMPOSITES PANELIZATION STRATEGIES

4.1. SANDWICH CONSTRUCTION

Building envelope cladding systems often need to be waterproofed, insulated, structurally engineered for gravity and lateral loads, and accommodate movement within the panels and between adjacent panels. To accommodate these functionalities, architectural composite panels often require sandwiching a thermal foam core between thin sheets of composite material. The foam core provides both thermal resistance and shear stiffness and can be bonded rigidly to the face sheets. While high density foams are typically better structurally, their thermal insulation value is less favourable then other foams. This can be addressed by introducing shear resistant spacers combined with lower density foams which exhibit higher thermal resistance (Bechthold, 2008).

5. PROTOTYPE DEVELOPMENT PROCESS

The development process considered a design to manufacturing process (Figure 1). During the design process cost implications of applying composite panels were assessed through parametric modelling and optimization tools that can help to identify tolerances and curvature, identifying the scope of custom panelization areas and analysis of performance objectives. The material process involves a hybrid process of automated and manual processes to fabricate the mold, laminate fibers, structural and thermal layers. The design curvatures of the final panels are achieved through various forming processes using a digitally controlled reusable deformable bed as a casting surface.

5.1. FABRICATION PROCESSES

This research accommodated a variety of existing digital fabrication processes.

5.1.1. MATERIAL AND FORMING

Potential materials for architectural surfaces are based on the matrix materials (e.g, metal, polymer, ceramic) and fiber for structural or non-structural applications. While a concrete based ceramic matrix of cement is the most common building material for complex shaped panel construction. This research examined examples of composites including polymer matrix composites (PMC), glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), pultrusions, metal matrix composites (MMC), ceramic matrix composites (CMC), and carbon-carbon composites (CCC).

Those materials can be pre-formed (forming and casting) or post-formed (deforming). Currently the majority of large scale architectural projects using complex panel shapes have been produced using pre-formed concrete panels and post-formed metal sheet panels. Composites such as fiber reinforced polymers have also been used to create complex shaped panels. In most of these cases pre-formed single-use molds have been used to create the FRP panels (Blonder & Grobman, 2015).

5.1.2. ADDITIVE TECHNIQUES

Additive techniques for complex shaped components often utilize 3D printing techniques. A small scale example is a fiber 3D printer (MARKFORG3D[2]) which incrementally deposits fiber to create surfaces and solid components. While size limitations prohibit large scale applications of 3D printing techniques, CNC fiber placement heads are utilized in the production process of large complex shaped sail products, adopting additive techniques. This technique is intended to be applied subsequently in this research to automate the fiber layering during the laminating process for the proposed prototype.

Non-fiber additive techniques such as stereolithography, laser sintering, fused deposition modelling, polyjet and 3d-printing have been used in commercial manufacturing to produce plastic prototypes and machine components (Strauss, 2012). These techniques primarily utilize plastics or resins that are heated or cured to create bonded layers. These bonded or fused layers of plastic although relatively strong for smaller components generally lack the stiffness and bending resistance needed to perform as a building scale architectural panel.

Direct metal fabrication (DMF) additive techniques such as power feed process, laser engineered net shaping, direct metal deposition, power bed process and electron beam melting utilize lasers or electron beams to melt deposited metal particles to create prototypes for complex shaped machine parts (Strauss, 2012). Both plastic and metal additive methods have not found commercial success in producing large scale architectural panels. This is primarily due to the issues of build volume, speed and cost. Most of the tools for additive techniques have build volumes that are unable to accommodate a large scale building panel such as a 1.5m x 3m panel. Although some newer equipment such as the VX4000 by Voxeljet have the build volume to create a large scale building panel the type of plastic materials available for use still are not well suited for thin large scale exterior panels. Speed in additive techniques has also been a challenge especially for larger objects that still require high resolution (Castaneda, Lauret, Lirola, & Ovando, 2015). When comparing the set up and production time for additive techniques versus deformation techniques such as roll forming for metal sheet goods used in building panels, additive techniques require at least an order of magnitude greater time to complete production.

5.1.3. SUBTRACTIVE TECHNIQUES

Subtractive methods used during milling and routing parts from larger material blocks are often applied to create desired complex surfaces for mold surfaces or sandwich core material (foam or honeycomb). This process relies on computer-numerically-controlled (CNC) equipment. Subtractive techniques such as laser cutting, water-jet, hot-wire, and multi-axis milling have often developed from automating the manual process of two-dimensional production techniques (Castaneda et al., 2015). In general contouring of complex three-dimensional surfaces is geometrically reduced to a stacked series of two dimensional subtraction operations that can be procedurally burned, carved or cut by a computer controlled tool arm. The inherent draw back to this method is the waste of material and the time needed to cut through each layer. Materials with greater hardness, density and strength typically require more time to slowly subtract the material. CNC milling techniques have been extensively used for large stone fabrication, especially for countertops and decorative relief panels. Subtractive techniques to directly produce complex double curved panels though have had very limited commercial application due to time required to mill large depth panels and the associated material waste (often directly impacting cost) of large panels with significant depth change.

5.1.4. PRE-FORMING TECHNIQUES

Preforming techniques utilize subtractive methods to create the formwork or casting beds for curved surfaces. These processes are often used to cast concrete into complex shapes. Often the process starts with CNC routing a foam bed to create the negative mold shape and is followed by casting cementitious fiber reinforced material into the negative mold to create the desired positive surface.

Because the process of creating and molding uniquely shaped components is highly time and labor intensive, this process would only be viable if there are large numbers of repetitive components that can be repeatedly cast to reach economies of scale.

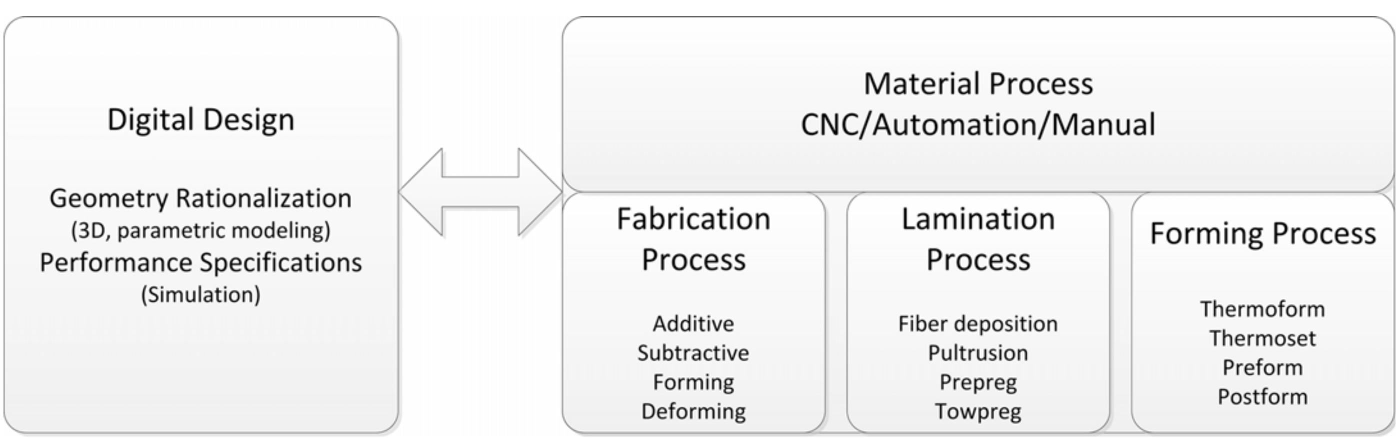

Figure 1. Digital design and manufacturing process of architectural composite panels.

5.1.5. POST-FORMING TECHNIQUES

Post-forming processes often utilize heating methods to plastically deforming sheet materials by pressing them against another object to create a three dimensional surface. Thermoforming and vacuum forming have been used to create architectural surfaces primarily out of plastics. The benefit of this technique is that it reduces fabrication time by removing the curing process typical of forming techniques. The same limitation of creating a formable bed or negative surface used in forming techniques is required in this process. Large local depth variations and sharp changes in surface direction may also not be well resolved using deformation techniques due to uneven plastic deformation of the sheet product causing local tearing or thinning which may result in unacceptable panel weaknesses.

In the last decade recent improvements in sheet metal fabrication techniques offer insight into possible strategies for composite architectural panels. Roll forming has long been used to create metal panel products such as corrugated steel. The ridges and deformations created through roll forming have generally been used to add rigidity by imparting an improved cross-sectional geometry to a linear product whether being a sheet good or cold rolled structural section. Roll forming has also long been used to create single curved metal sheet goods that have been used in building cladding.

For more complex three dimensional shapes requiring non-uniform radii or double curved surfaces metal sheet fabrication has required the creation of die or CNC milled upper and lower forms and often hydraulic presses to provide uniform pressure on the sheet. These forms are expensive and time consuming to create and are traditionally only utilized for mass producing a repeatable product such as an automotive body part (Alonso-Pastor, Lauret-Aguirregabiria, Castañeda-Vergara, Domínguez-García, & Ovando-Vacarezza, 2014). Thus most metal cladding of complex three dimensional shapes have typically relied on geometric panelization that limits the panels to single curved and flat tessellated pieces.

Recently sheet metal fabricators have created two and three roller processes that utilize a flexible set of curved rollers that can create double curvature sheet metal surfaces such as saddle and torus shapes. The drawback to this is that these techniques currently have relatively small maximum deformation capacity perpendicular to the length of the material due to the roller design. The state-of-the-art in complex geometry metal sheet fabrication is multipoint stretch forming. The term multi-point denotes that the forming surfaces are actually a grid array of computer controlled points that can be raised and lowered as needed to create a surface shape (Lee & Kim, 2012). This technique utilizes two multi-point beds (one below and one above the metal sheet) to press the sheet. At the same time to reduce wrinkling and dimpling the sheet is stretched by clamps on two ends to maintain the desired geometric boundaries (Cai, Li, & Lan, 2012; Wang, Li, & Cai, 2014).

5.1.6. RESEARCH NEEDS FOR FORM BEDS

The dimensional and cost limitations of current additive and subtractive digitally driven fabrication techniques indicated the need of research for improved forming techniques of composites. The cost of creating custom molds for negative surfaces poses significant limitations during the forming process. Thus making fiber composites a less attractive product for architectural projects as it increases the overall cost including lead times, packaging and shipping of finished products to job sites.

To address the shortcoming of single-use custom molds, investigations focused on developing a reusable rapidly deformable bed for pre-forming and post-forming operations which could reduce the material and fabrication time needed to make the surface negatives. This is similar in essence to the multi-point method to create a deformation bed used in sheet metal fabrication.

5.2. PROTOTYPING

5.2.1. VACUUM FORMING STUDY

Initial experimental studies were conducted to explore vacuuming forming with 1/16" sheets of Plexiglas over a laminated cardboard forming bed. Cross sections of cardboard were laser cut to create a three dimensional surface with each layer of cardboard standing vertically on its edge to allow for air to be pulled through the assembly. The cardboard pieces were mechanically held together to form the bed. It was identified that vacuum forming requires large forces to be exerted on the forming bed and accordingly require high strength resistive capabilities to support the forces generated during the vacuum forming. High strength resistance in a deformable bed can be achieved through a mechanical lock system or pneumatic actuators. Forming large

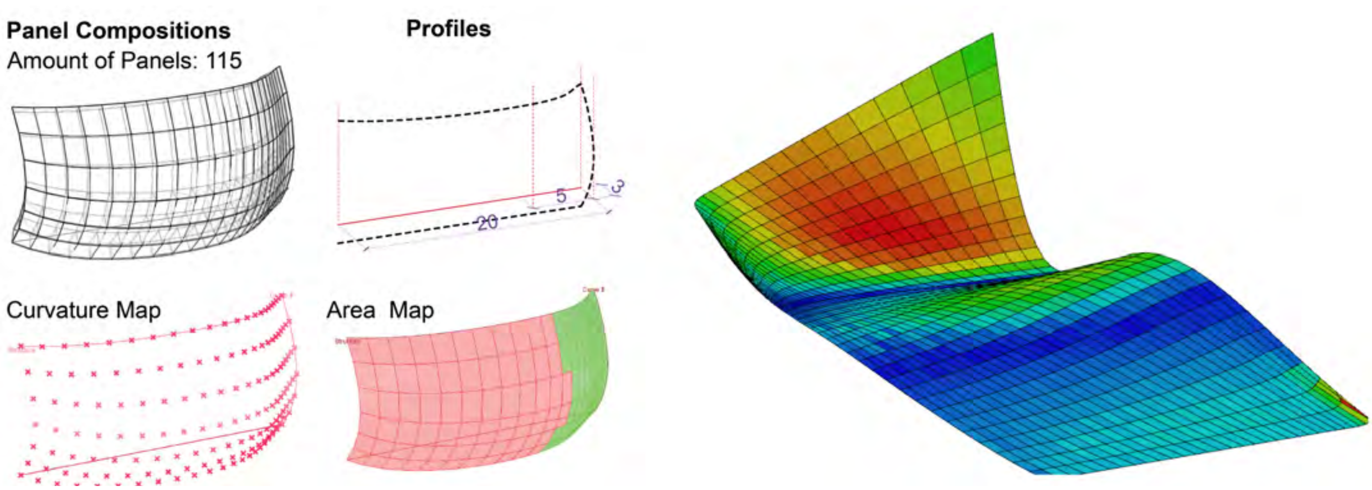

Figure 2. Double-curved panelization model and planarity analysis.

sheets via vacuum forming techniques may require large sacrificial molds which may be costly and challenging to produce.

However, on a larger scale vacuum bags are used to laminate large scale sheets instead of molding composite sheets into desired geometry. To laminate using vacuum bags, the sheet material would be tension stretched over a mold and vacuum compressed with fibers that are laid on top of the membrane material. Creating the required vacuum force and heat while maintaining control over the product quality may be achieved at larger scale for up to 500 square meters as seen in the production of sails (Pearson, 2010).

As a next step the team started to investigate mechanisms for an adjustable form bed for resins, epoxies and fiber reinforcement placement.

5.2.2. GEOMETRIC STUDIES

3D models of double- and single-curved panels' geometries were generated to study panelization strategies from larger architectural surface applications. The left portion of Figure 2 shows a model of a double curved surface made from 115 panels. The highlighted areas in green were calculated to identify target areas with larger deformation curvatures that would be adequate for custom composite panel production. Curvature analyses can be used to evaluate and plan for composite fabrication to maximize time and production advantages. Using geometry rationalization and planarity analysis tools such as Evolute, a Rhino 3D plugin, double curved surfaces can be panelized using parametric rules to limit maximum slope and deformation within panels to improve ease of fabrication. The right side of figure 2 shows and example of planarity analysis.

5.2.3. MOLD BED USING MUSCLE WIRE

The research explored two digitally driven deformable bed techniques to replace the standard disposable CNC cut foam beds. The first alternative utilized shape memory alloy (Nickel Titanium or nitinol wire) – muscle wire. Nitinol has the unusual ability to perform a solid-state transformation (known as a martensitic transformation) between two defined states as a result of changes in temperature which can be incurred through an electric current. At lower temperature the wire elongates and at higher temperature the wire shortens returning to its original shape.

The team explored various nitinol weave patterns (i.e., rectilinear, circular) to study deformations to be used in a deformable bed. Results proved to be unsuccessful because of the small amount of displacement they created to achieve a desired form. Relating specific weave pattern with desired shapes also turned out to be challenging and this approach was abandoned.

5.2.4. MOLD BED USING MECHANICAL ACTUATORS

A mold bed with high surface variation for the resin, fiber, and foam core, was developed adopting a mechanically driven solution using solenoid actuators controlled through a microprocessor (currently the team has adopted the use of an Ardunio microcontroller) with a relay array.

This allows for a surface resolution determined by the number of actuators and the stepping height of each actuator. For the initial prototype attempt simple push pull actuators are being used to create a three height actuator array with each actuator being able to be addressed individually. Figure 3 shows the actuator array. The array is designed to be covered with a plastic or silicone membrane that holds the resin or epoxy matrix. Preliminary tests have shown that these actuators have ample load capacity for supporting our expected casting activities. The interface control is achieved through a Rhino 3D/Grasshopper Firefly plugin which allows direct control of the actuators from an interactive digital surface geometry.

5.2.5. FIBER COMPOSITE LAYERING AND FORMING

The team experimented with glass fiber fabric and epoxy resin to create fiber reinforced composite sheets which would be formed on the mechanically deformable bed. The vacuum lamination process requires a tight seal around the perimeter of the bagging film which informed the geometry and design of the deformation bed apparatus.

6. CONCLUSION

This paper discussed the development of a digitally driven fabrication framework for complex-shaped architectural composite panels. Results from preliminary explorations of a deformable bed for forming composite panels were presented. Literature review showed growing interest for composites use in architectural envelope panel applications, particularly in complex shaped projects, and the need for design research of associated production systems, dynamic mold processes and materials. Prototyping efforts helped to understand core aspects of fiber composites, molding processes and tertiary aspects including electric circuits and actuation mechanisms.

Future work will focus on refining the mold bed platform involving curvature resolution control, mold bed attachment details, and in-depth explorations of various fiber composite material properties and applicability of pre-forming and post-forming techniques. The prototyping research of the deformation bed will be expanded to include design criteria of a fabrication space and examine the work flow from raw fiber materials to finalized products that can be fabricated onsite in a mobile containerized facility.

Recommendations for future research and a roadmap for commercialization will be established. This research project is scheduled to continue through the remainder of the 2015-2016 academic year with early trials of casting materials for panel creation currently in progress.

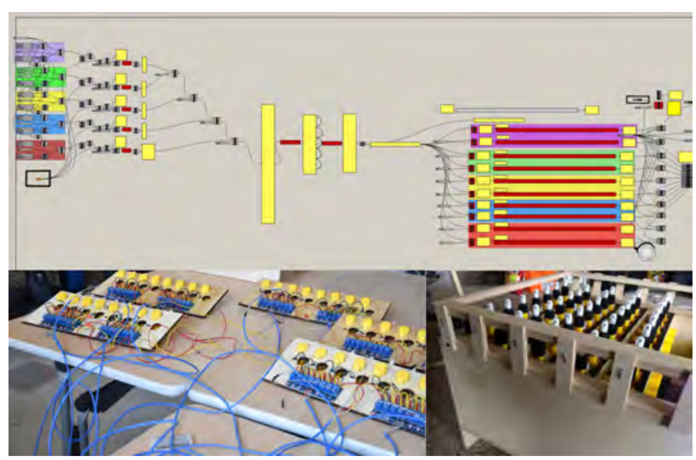

Figure 3. Digital control of solenoid actuator array for deformable bed experiments

Figure 4. Flexible, reconfigurable deformable bed mold

Figure 5. Fiber composite sample

ACKNOWLEDGEMENTS

This research was funded through the MAG Composites Institute at Philadelphia University. The writers appreciate the help of Philadelphia University research assistants Philip Rivera, Jesse Smith, Bruce Garnett, Adrienne Remener, and special assistance from doctoral candidate Christopher Anderson on Tailored Fiber Placement Technology.

ENDNOTES

1. http://www.compositesworld.com/articles/composites-and-architecture-blog
2. https://markforged.com/.

REFERENCES

Alonso-Pastor, L., Lauret-Aguirregabiria, B., Castañeda-Vergara, E., Domínguez-García, D., & Ovando-Vacarezza, G. (2014). Free-Form Architectural Façade Panels: An Overview of Available Mass-Production Methods for Free-Form External Envelopes *Construction and Building Research* (pp. 149-156): Springer.

Bechthold, M.: 2008, *Innovative Surface Structures: Technologies and Applications*, Taylor & Francis.

Blonder, A., & Grobman, Y. J. (2015). Design and fabrication with fibre-reinforced polymers in architecture: a case for complex geometry. *Architectural Science Review* (ahead-of-print), 1-12.

Cai, Z.-Y., Li, M.-Z., & Lan, Y.-W. (2012). Three-dimensional sheet metal continuous forming process based on flexible roll bending: principle and experiments. *Journal of Materials Processing Technology*, 212(1), 120-127.

Castaneda, E., Lauret, B., Lirola, J., & Ovando, G. (2015). Free-form architectural envelopes: Digital processes opportunities of industrial production at a reasonable price. *Journal of Facade Design and Engineering,* 3(1), 1-13.

Chudley, R. G., Roger. 2010. *Building Construction Handbook - Incorporating Current Building and Construction Regulations* (8th Edition).

Eigensatz, M., Kilian, M., Schiftner, A., Mitra, N., Pottmann, H., and Pauly, M.: 2010, Paneling architectural freeform surfaces, *ACM SIGGRAPH Tansaction on Graphics*, 29 (3), Available from: < http://graphics.stanford.edu/~niloy/research/paneling/paneling_sig_10.html> (accessed 1 December 2015).

Fernandez, J.: 2006, *Material Architecture*, Architectural Press.

Glymph, J., Shelden, D., Ceccato, C., Mussela, J., and Schober, H.: 2004, A parametric strategy for free-form glass structures using quadrilateral planar facets, *Automation in Construction*, 13, 187–202.

Kolarevik, B.:2003, *Architecture in the Digital Age: Design and Manufacturing*, Kolarevik, B. (eds.), Taylor & Francis.

Ku, K., Pollalis, S., Fischer, M., Shelden, D.: 2008, 3D model-based collaboration in design development and construction of complex-shaped buildings, *ITcon* 13, Special Issue Case Studies on BIM Use, 258-285.

Lee, G., & Kim, S. (2012). Case study of mass customization of double-curved metal façade panels using a new hybrid sheet metal processing technique. *Journal of Construction Engineering and Management*, 138(11), 1322-1330.

Lynn, G. and Gage, M.: 2010, *Composites, Surfaces, and Software*, Yale School of Architecture.

Pearson, W.: 2010, North Sails Three-Dimensional Laminates: The shrinking Space between Composites and Textiles, *Composites, Surfaces, and Software*, Lynn, G. and Gage, M.: (eds.), Yale School of Architecture.

Schodek D. L., Bechthold M., Griggs K., Kao K. M., and Steinberg M.: 2005, *Digital design and manufacturing : CAD/CAM applications in architecture and design*. John Wiley & Sons, Hoboken.

Strauss, H. (2012). *AM Envelope: The Potential of Additive Manufacturing for Façade Construction* (Vol. 1): TU Delft.

Wang, D., Li, M., & Cai, Z. (2014). Continuous-forming method for three-dimensional surface parts combining rolling process with multipoint-forming technology. *The International Journal of Advanced Manufacturing Technology*, 72(1-4), 201-207.

Whitehead, H.: 2003, Lays of form, *Architecture in the Digital Age: Design and Manufacturing*, Kolarevik, B. (eds.), Taylor & Francis.

Yun, Y. and Schodek, D.: 2003, Development of boundary structures for complex-shaped buildings, *Journal of Architectural Engineering*, 9 (1), 18-25.