Towards digital containerized factories of composite architectural panels for complex shaped buildings

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ABSTRACT**:** Complex building shapes requiring double curved or deformed surfaces can be a difficult and expensive aspect of design and construction for façade materials. Most often building envelopes that create complex shapes do so by a compilation of many smaller elements to create a larger object or form. These elements are frequently prefabricated in specialized workshops that allow for the use of digital fabrication tools that can reference 3D design models. Some of the difficulties that arise in this type of process are long lead times, extended material travel distances (to and from digital workshops) and reduced flexibility in overcoming on-site construction variations. Over the past year the authors researched new methods using fiber-reinforced composite sandwich panels to produce on-site digitally fabricated curved panels for use in complex shaped buildings. This research examined the material properties, manufacturing methods and fabrication techniques needed to develop a proof of concept system using readily available production technology that can be packaged in a mobile containerized facility for on-site panel production. This paper will present production materials, methods, assembly techniques and design proposals for a proof of concept digital containerized panel factory. Comparison of production methods will be presented and recommendations for future work will be included.

KEYWORDS: Digital Facade Fabrication, Fiber-Reinforced Plastic, Mobile Fabrication

INTRODUCTION

Off-site fabrication has been typically identified with various benefits including cost reduction, enhanced construction efficiency, and improved quality. Cost reduction is related to reduction of waste, rework, manual handling, labor productivity, etc. (Pasquire et al., 2004). Construction efficiency benefits from the possibility to minimize joints, maximizing the size of elements, minimizing the disparities between trades and minimizing construction tolerance. Despite the many benefits of off-site fabrication, there have been growing concerns about the increasing cost of transportation and packaging, size limits of shipping units, particularly in the case of complex shaped panels, ergonomic issues during site erection of panelized components which prioritize packing efficiency over on-site storing and erection sequencing. A number of recent projects have adopted near-site (Ku et al. 2012) or on-site fabrication (e.g., R-O-B mobile fabrication unit[i], Facit Homes[ii]) approaches which explore a paradigm shift from centralized manufacturing to distributed manufacturing. Near-site fabrication involves preassembling modular units such as integrated mechanical, electrical, and plumbing ceiling racks in warehouse spaces near the jobsite. Components such as HVAC ducts, piping and electrical conduits, etc. are shipped and preassembled in a warehouse into modules. This simplifies on-site assembly issues including trade coordination, quality control, tolerance issues in addition to shipping and schedule. On-site fabrication may involve building temporary production plants (e.g., concrete batch plant) or mobile factories. Cold-formed sections from steel sheet, strip, plates flat bars in a roll-forming machine, press brake, or bending brake operations, allow easy fabrication and mass production (Gann, 1996). A Virginia company produces 25-foot containers accommodating galvanized steel panel-forming machine and hydraulic guillotine which are shipped to job sites to transform coils. A London based firm, Facit Homes ships a CNC router in a shipping container to mill modular elements with snap on connectors to assemble the building onsite. The advancements of digital design and manufacturing offer opportunities to combine this containerized fabrication idea with a digital process.

The paradigm shift to containerized fabrication offers opportunities to produce non-volumetric preassembled units. These units can be skeletal, planar or complex panel systems or, cladding panels. Fully enclosed spatial units such as bathroom pods cannot be built in these container units because of the limited space. Thus fully enclosed spatial units would not be considered for mobile production. The idea of containerized factories assumes a linear process where material is entered as an input into this mobile unit, processed by equipment, and produced as an output. The advances in materials such as composites, provide fertile ground for research and development of architectural materials and systems which can potentially take advantage of such containerized processes.

The authors are presenting explorations of a prototype for the production of complex shaped architectural composite panels. The goal is to identify the requirements and specifications of the production equipment and production unit. The application of this unit is on façade systems as it is one of the crucial design features that architects and builders attempt to achieve cost effectively, satisfying an owner's goal of exploiting the enclosed space to maximum advantage (Chudley and Roger, 2010). In this article, first a review of existing fabrication methods is discussed. Then preliminary experiments and parameters of a production unit are presented.

1.1. General overview of existing methods

To help develop a new method for producing complex three dimensional architectural panels for use in building envelope assemblies this research began by reviewing the existing practices typically employed in current or recent architectural construction. By examining the difficulties and most pressing issues of existing methods the research team sought to develop new manufacturing techniques to address the most significant obstacles facing more widespread access to complex three dimensional panels.

1.2. Material and forming

To begin understanding the development of complex three dimensional architectural panels one can conceptually categorize techniques based on two primary elements. One element is the choice of material for the architectural surface. This material could be wood, plastic, glass, steel, concrete or any material that has already been used to make complex three dimensional architectural surfaces. The other element is the choice of a deformation or forming technique. This can be broadly sub-categorized into four methods: additive, subtractive, formed and deformed.

1.3. Additive

An additive technique for a complex three dimensional architectural surface could be similar to 3D printing and might utilize many smaller identical elements systematically assembled to create a larger surface. This was not found to be a widespread technique due to the size limitations of 3D printing and the lack of appropriate materials available for use in architectural surfaces that would be expected to be durable in exterior weather conditions. More traditional additive techniques would be to utilize many dissimilar pieces to construct a framed surface element that is then mounted or fastened to a larger structural support. This would be more akin to typical rainscreen panels or facades that utilize a finished material on the outer surface and a hidden structural system on the rear side. While this technique is widely used for flat surfaces using rigid sheet goods, and even single curved surfaces (such as those made from composite metal panels), they are rarely used for more complex double and triple curved architectural surfaces due to the extreme difficulty in fabricating an acceptably smooth double or triple curved surface from existing rigid sheet goods.

1.4. Subtractive

Subtractive methods essentially start with a larger mass of material and systematically remove material to carve out the desired complex surface. Digitally driven subtractive processes often use Computer Numerical Control (CNC) routers to remove material to create the desired surface. This technique has been used to create low relief architectural panels, particularly of stone materials that cannot be cast. One of the difficulties of this technique though is the large amount of waste and cost from the subtractive process. Usually this waste material cannot be successfully recycled for further use in the subtractive process. Another weakness of this method is the time needed to fabricate the surface. Since durable exterior building materials often are dense or have high surface hardness, subtractive process must slowly cut away the material. Thus a 4'x8' stone panel with one or two inches of relief depth will take hours if not days to complete and only provide minimal depth or overall curvature.

1.5. Forming

Forming techniques often use subtractive methods to create formwork or casting beds for the creation of complex three dimensional shapes. This is akin to making a plaster or concrete pour into a complex form so that when cured the formwork can be removed to reveal the desired surface. This is presently the most frequently used technique in producing complex three dimensional architectural panels that have more than a single curve within the panel. Most often this is produced by first CNC cutting a foam bed to become the negative or the casting surface and then casting high strength cementitious fiber reinforced material against the negative to create the desired positive surface. While foam and cementitious materials are relatively cheap, the process is laborious and time intensive since each foam bed is essentially treated as a single use disposable formwork and each panel must be cured and surface treated after being released from it's negative. Thus time is spent on creating the forming bed, casting the material and then surface finishing the material once cured. Injection modeling, often used in product and furniture manufacturing uses more durable forming surfaces (often CNC cut aluminum molds) but requires a high quantity of repeated elements to be economical and thus has not been appropriate for non-uniform or non-repetitive architectural surfaces.

1.6. Deforming

Deformation processes most often utilize a sheet good that can be heated up and then plastically deformed by pressing it against another object to create a complex 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 to occur that may result in unacceptable panel weaknesses.

1.7. Form bed as limiting factor

Given the dimensional and economic limitations of current additive and subtractive digitally driven fabrication techniques in the manufacturer of complex three dimensional architectural surfaces and the more frequent use of forming and deforming methods in state of the art architectural facade installations the forming bed was identified as a significant target for research in improving fabrication ability. In both forming and deforming techniques, the creation of a disposable form bed via CNC methods places a large amount of material, space and time devoted to the creation of the negative surface rather than the end product which is the surface positive. The time, space and materials required to create the form beds and perform the forming/deforming has limited production of complex three dimensional façade panels to off-site fabrication labs which has increased lead times and cost related to packaging and shipping finished goods to job sites.

Shipping costs for finished goods sent to a job site almost always are more expensive than shipping costs for raw goods due to the higher level of care required in handling and inefficiencies inherent in the non-standard sizes of finished goods. Thus it should be advantageous to be able to site fabricate complex three dimensional panels on demand using a technique that allows for a reusable form bed that can create multiple unique three dimensional surfaces. Thus the concept of developing a reusable rapidly deformable bed for forming and deforming operations was identified by the research team. This would remove the material and fabrication time needed to make the surface negative and would then only require that the majority of the raw goods to be shipped are those that are part of the end product. This should make mobile fabrication of complex three dimensional architectural façade panels less expensive and more readily available.

1.8. Material exploration

This research also included exploration of materials that would be appropriate for site fabrication via forming and/or deforming methods that could be coupled with a deformable bed. Material goals were that the chosen material should be commercially widely available, durable in exterior exposure scenarios, be easily connected to fasteners and framework for structural support, easily transportable, have low site energy demands during fabrication, cure or deform rapidly, be lightweight, could be used in a multilayer assembly (to add insulation), and be dimensionally stable over time. As such the research team examined existing plastic sheet goods, cementitious materials, fiber reinforced resins, and types of reinforcing fibers to develop a proof of concept system prototype for the fabrication of complex three dimensional architectural façade panels.

2.0 METHODOLOGY

2.1. Vacuum forming study

To gain perspective on the use of forming and deforming methods small experimental studies were conducted by the research team using existing techniques. Vacuuming forming was one of the first methods explored and 1/16" sheets of Plexiglas were used over a laminated cardboard forming bed. Numerous sheets 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. Fig. 1 shows the cardboard assembly without plastic and Fig. 2 shows a 16th inch thick sheet of Plexiglass vacuum formed onto the cardboard bed. While as a small one foot by one foot demonstration this may be simple and easy to accomplish scaling this to the size of a larger four feet by eight feet architectural panel may not be practical since much thicker plastic materials would be needed and assembling the bed would be time intensive. Creating the required vacuum force and heat while maintaining control over the product quality may also prove to be difficult at a larger scale.

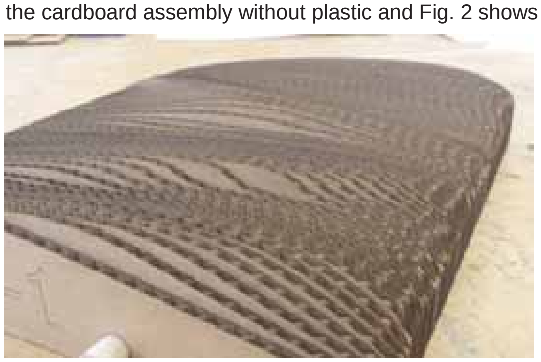
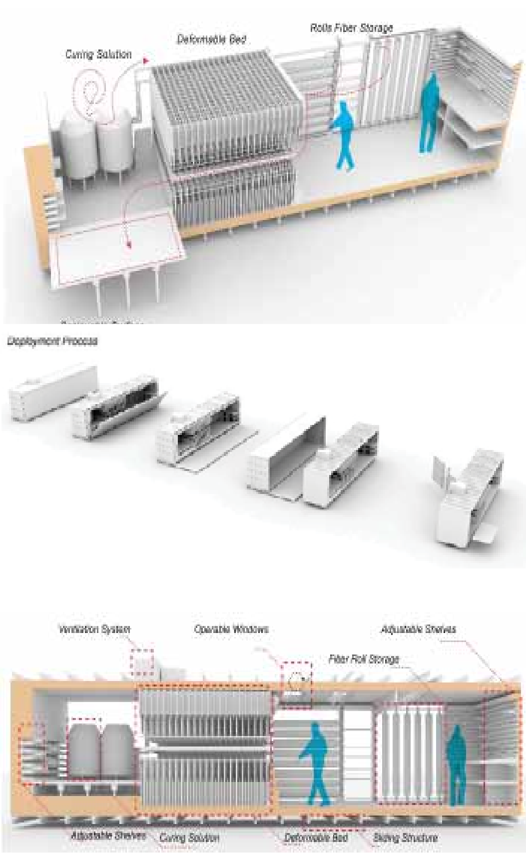


Figure 1: Cardboard test forming bed (Jesse Smith 2014)

Having identified that vacuum forming requires large forces to be exerted on the forming bed the research team surmised that any deformable bed system using vacuum forming would require high strength resistive capabilities to support the forces generated during the vacuum forming. High strength resistance in a deformable bed would most likely require either high strength motors,

Figure 2: Plexi Vacuum formed on cardboard (Smith 2014)



pistons or actuators and thus require a high amount of energy during the process. Similarly other deformable techniques generally would require either high energy use for deforming the material and or substantial heating of materials to promote thermoformed deformations. This led the team to steer away from deformation techniques and instead the team focused on methods of forming the architectural surfaces using materials such as resins, epoxies and fiber reinforcement that could be placed on top of a deformable bed.

2.2. Projecting mobile implementation

While exploring the forming methods and materials the team also concurrently studied simulated outcomes in regards to creating a mobile fabrication facility. Virtual models and rendering were created to begin to understand the layout and processes that would be needed. This was done to help guide the research towards panel fabrication methods and techniques that would be compatible with the space and resource limitations that would be present in a mobile facility. This also helped the team imagine how the various stages of the fabrication process could be organized to increase panel production and raw material processing capacity. A starting point for the design of the mobile facility was a 40 feet long shipping container. It was quickly apparent that good circulation, ventilation and external power connection would be critical for the mobile facility to operate effectively. Fig. 3 shows a sequence of renderings based on these mobile implementation sketches.

2.3. Virtual panels

To also help in understanding the needed outcomes for a deformable bed and proposed complex shaped panels such as what might be a typical curve or slope needed in a façade panel, the team also generated three dimensional models of double and free-form curved panels that were part of larger architectural façade assemblies. Fig. 4 shows some early studies in taking three dimensional surface models and developing panelization strategies to create a grid of panels that could be made on a deformable bed using square or rectangular edge boundaries. Fig. 5 is a model of a double curved surface made from 115 panels. Fig. 6 is a model of a free-form surface with increased resolution using 231 panels.

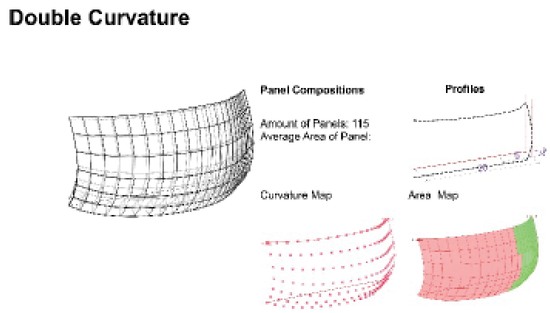


Figure 3: Double Curved Panelization Sketch (Rivera 2014)

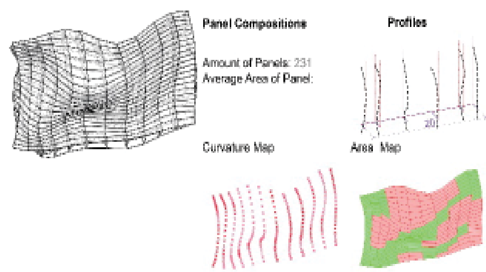


Figure 4: Free-Form Panelization Sketch (Rivera 2014)

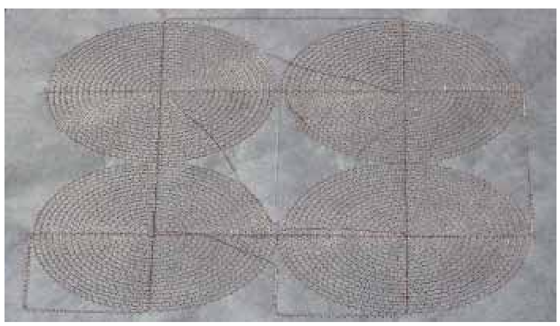


Figure 5: Mobile Fabrication Sketches (Philip Rivera 2014)

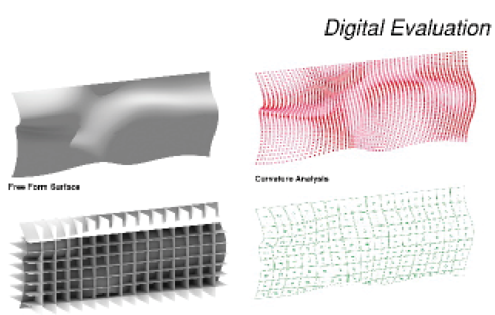


Figure 6: Façade Surface to Panelization (Rivera 2014)

The team imagined that mobile fabrication would not supplant traditional off-site fabrication but could be leveraged to create on-site panels for façade areas with highly demanding edge alignment conditions. Thus if a panel has large areas of edge deformation these panels might have greater failure rates during installation (due to gaps that are too wide or neighboring panels that don't properly align). These panels then could be specifically targeted for onsite production after the majority of other simpler panels have been installed. Then laser measurements techniques using LIDAR equipment could provide actual dimensions that could be used to adjust the digital models before fabrication. This could drastically reduce the turnaround time for pieces that are sent back due to poor fit, misalignment or incorrect fabrication. Figures 5 and 6 show highlighted areas in green that were calculated to have the greatest surface deformation and would be likely target areas for on-site fabrication. In this way design and fabrication teams could evaluate and plan for fabrication at both onsite and offsite facilities to maximize their time and production advantages.

2.4. Deformation Bed via Nickel Titanium

The creation of a digitally driven deformable bed that could replace the standard disposable CNC cut foam beds with something that could be reused and quickly reformed led the research work into the exploration of two distinct alternatives. The first alternative was the use of Nickel Titanium or nitinol wire, also known as memory 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. This change in temperature is most often created by heating the wire through an electric current. Essentially at lower temperature the wire can be elongated and deform, at higher temperature the wire shortens and returns to its original shape. By controlling the temperature via electric current through the wire a controlled deformation of the wire can be created. When using the wire as a woven component on a textile surface the nitinol wire can cause local area deformations that produce three dimensional surfaces.

One of the team members was already familiar with using nitinol in textiles and was able to create early stage examples of nitinol woven into a fabric to create a deformable bed. Fig. 7 shows an example of a circular pattern using memory wire and Fig. 8 shows an example of a rectilinear pattern also using memory wire. These early attempts while exciting and innovative proved to be highly restricted in the amount of load they could support and thus proved to be currently unsuitable for supporting the loaded needed in forming and casting a resin or epoxy panel for an architectural façade. Perhaps if the nitinol was of thicker diameter and the spacing was tighter increased loads could be supported, but this was beyond the scope the research project at that time.

Figure 7: Actuator Deformation Bed (Anderson 2014)

2.5. Deformation bed via actuators

Given the need to create a panel with high surface variation and a casting surface that could support the weight of resin and other potential façade materials the team focused on the creation of a mechanically driven solution using motors and/or solenoid actuators that could be digitally driven through a microprocessor with a relay array. This would allow for a surface resolution that could be closely pair with the number of actuators used as well as the stepping height of each actuator. For the initial attempt simple push pull actuators are being used to create a three height actuator array with each actuator being able to be addressed individually. Fig. 9 shows the actuator array draped with a sheet of clear plastic before casting resin or epoxy has been applied. Preliminary tests have shown that these actuators have ample load capacity for supporting our expected casting activities.

3.0 RESULTS & DISCUSSION

This research project is scheduled to continue through the remainder of the 2014-2015 academic year and early trials of casting materials for panel creation on the actuator driven deformable bed have recently begun. The results from these trials as well as a working proof of concept mock-up of a process to rapidly produce a complex three dimensional panel is expected to be shared via publication in the 2015-2016 academic year. We expect to also develop recommendations for the materials that are well suited for this process and methods to improve the next iteration or prototypes of rapidly deformable casting beds that can be utilized in mobile panel fabrication.

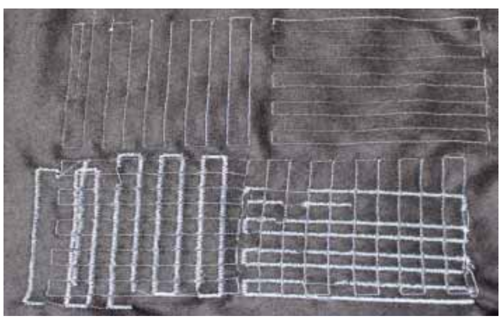


Figure 8: Nitinoal rectangular pattern study (Anderson 2014)

The research team has discussed improvements and alternate methods that could be targeted for future research and development. One proposed method is to use spray foam through a computer controlled flow nozzle that is mounted to the moving arm of a CNC platform. This would allow for insulation to be added on the back side of the panel surface. This technique could also work well to increase curvature and pattern resolution. By using a slow rise spray foam and a laser measuring device the addition of spray material could be calibrated to create geometries and forms that could be added on top of the deformable bed and become the forming bed for the resin/epoxy panels. In addition the CNC router could be used to make minor alterations to the spray foam bed before casting and also could be used to engrave patterns or information on the outer panel surface. In this way a high resolution deformation could be created with very little material waste and with far less time than using CNC exclusively. Essentially the actuator bed would provide the base for large deformations, the spray foam would provide medium resolution deformation and the CNC process would allow for highly detailed resolution.

CONCLUSION

This paper discussed the development of a prototype of a containerized fabrication system for complex-shaped architectural composite panels. So far the investigations have concentrated on composite material as an emerging resource for architectural façade systems, the associated production systems, dynamic mold processes/materials, and tested various mechanical systems as actuators. Through trial and error, prototyping has involved system development for electric circuits, mold membrane, actuation systems, and fiber composites. Following work will determine the best material that provides cost effective and efficient mold construction. Alternate fiber composite material will be tested. Based on the findings of the prototype, recommendations for future research and a roadmap for commercialization will be established.

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ENDNOTES

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[ii] http://www.architectureanddesign.com.au/news/revolution-for-prefab-homes-moving-digital-fabrica