ABSTRACT

A textile hybrid system is based upon a structural logic that generates form in the relationship between an elastic textile surface and the bending resistance of fiber-reinforced composite material. Such structures are always discretized as the materials are born of highly specialized manufacturing processes: weaving or knitting for manufacturing textiles and pultrusion for the production of the particular fiber-reinforced composite elements typically utilized in textile hybrid structures.

The research described in this paper embeds properties of both elastic textile and bending-resistant composites within a single material structure. This is accomplished through a composite forming process which utilizes pre-stressed textiles integrated with isolated regions of stiffened material. The design of material behavior is utilized in both the forming process and the implementation of the material system itself. By calibrating curing time and the influence of the pre-stressed textile, complex 3D forms are generated without the use of complex 3D formwork (preforms). The resulting material systems have an inherent textile hybrid nature while also, as composites, offer high degrees of flexure. A series of studies depict the potential in forming complex 3D surface structures, and utilizing the ductile nature as reconfigurable material systems.
INTRODUCTION

A strong attraction to fiber-reinforced composites, as a material system, is their ability to be designed for any form, where the primary constraint is in fabricating the formwork, also referred to as the preform (Bechtold 2008). Robotically driven techniques for fiber-layup, in particular fiber-winding, minimize the need for the preform to be an exhaustively produced replica of the target composite surface, as shown in the ICD/ITKE Research Pavilion 2012 (Schwinn et al. 2013). Fiber placement and density are equal and critical factors to shaping the continuous structural form. This particular precedent is relevant as it begins to disengage the typical post-rationalization process of first specifying geometric definition to later engineer material composition. In these cases, form and material composition are simultaneously configured.

This research looks to also expose fiber structure and the process of forming composites as variables that drive the definition of specific material morphologies. This work builds upon research in textile-reinforced composites (TRC), where the reinforcement is tailored by the specific structure of a knitted textile (Hufenbach et al. 2011). This leverages capabilities in knitting where complex 3D textile structures and spacer fabrics can be produced with continuous fibers (Abounaim et al. 2010; Cebulla, Diestel and Offermann 2002). The research described in this paper introduces the use of pre-stress in the textile reinforcement to drive material formations. This includes the consideration of curing time in relation to composite stiffness to manipulate the degree of 3D material formation. The use of formwork is dismissed as the presence of pre-stress provides a post-forming process to transform an initially flat geometry to a complex 3D configuration. This is being termed pre-stressed Textile-Reinforced Composite or \( \text{pTRC} \). Unique to this approach is the design of material behavior for influence during the process of material forming. A series of studies, developed with the Master of Science in Material Systems program at the University of Michigan, exploits various aspects of this material forming process to produce unique spatial and structural material compositions.

INTEGRATED TEXTILE HYBRID

Previous research has developed structural logics and design methods for textile hybrid systems utilizing glass fiber reinforced (GFRP) rods and textiles of varying composition (Ahquist and Menges 2013; Ahquist et al. 2013), as shown in (Figure 1). The textile hybrid is a structural logic which uses the equilibrium between elastically bent (typically linear) elements and tensile surfaces to generate a stable form (Lienhard et al. 2013). In carrying and directing load paths, all elements must have a designed fibrous condition (the textile component), whether woven/knitted structures or pultruded fiber-reinforced polymers (composites).

The \emph{hybrid} aspect refers to Heino Engel’s definition for the intermixing of structural actions (Engel 2007). This combines Engel’s traditional definition of form-active (tensile) structures, with the more recent introduction of the category of bending-active structures (Lienhard et al. 2012). As a structural system, a textile hybrid can be considered continuous as the movement and resolution of the forces occurs across all interconnected elements. In terms of topology, a textile hybrid is highly discretized between the textiles carrying tensile loads and the composite elements providing bending resistance. In this case, the interconnection of both materially similar and differentiated elements has to be strongly considered as they are often moments of significant force accumulation.

In the research described here, a method is developed for generating non-discretized material systems that internally house the textile hybrid form- and bending-active behavior. This is instrumentalyzed as a composite forming process, where structural action transforms the material system from a flat state to a pre-stressed 3D structure (Figure 2). Within a single assembly of multiple textile layers, certain regions are pre-stressed while other areas are formed as composites, all within a flat and fixed frame. Once the composite areas reach appropriate stiffness, the fused textiles are released from the frame. The pre-stressed areas subsequently induce a rebonding effect—activating the textile hybrid (form- and bending-active) nature of the material system. This is referred to in this research as a \emph{post-forming process}, where the curing time of the composite is considered in order to tune the relationship between the tensioned textile and the solidifying composite areas. Allowing the composite to continue its curing process after the rebonding effect helps to stiffen the resulting material system in a curved state. Ultimately, this creates a single material element which integrates both textile and composite properties, along with form- and bending-active behavior. Thus, the structural material logic is termed an integrated textile hybrid, whereas the specific material system is defined as a \( \text{pTRC} \), as defined previously.
The Delaminated Morphologies _TRC Prototype is designed as a multi-layer textile composite (left), utilizing areas of pre-stress to post-form the material system into a 3D spatial structure (right).

**FABRICATION METHODS FOR COMPOSITE FORMING PROCESS**

Producing the _TRC material system to generate 3D form from a flat condition necessitates a multi-phase manufacturing method that calibrates material processing and time. Pre-stress is utilized to activate the form-making process, driving the composite regions to take shape once they have cured to a critical degree of stiffness. The _TRC material system is comprised of two textile types: an elastic textile for pre-stressing and a densely structured textile for composite impregnation. After conducting a set of tests, it was concluded that a warp knitted polyamide mesh with elastic Spandex yarns provides the necessary strength and elasticity to drive the “rebounding” process in forming the composite regions.

For the composite regions, the textiles require a high fiber density in order to realize the correct fiber to resin ratio for gaining a desired stiffness. An array of material samples and tests examined different combinations of textiles and led to the choice of two types of weft knitted fabrics that have a stretchable structure of yarns as well as an appropriate thickness for resin consolidation, combined with the highly stretchable warp-knitted textile (Figure 4). A thin epoxy resin is used for the composite, mixed with “medium epoxy hardener” in a ratio of 3 to 1 in order to allow a twenty to twenty-five minute working time. The layup of textiles is set into a flat vacuum bed to aid the even distribution of epoxy throughout.

Unique to this process is the consideration of curing time and its relation to material stiffness. The moment at which the pre-stress is released to initiate the forming process (rebounding) is considered as a variable. This allows for an interesting relationship between geometry and stiffness. Depending upon when the pre-stress is released during the stage of curing, variable dimensionality in the material is produced based on great differences in stiffness of the composite areas (Figure 5). This is not a linear relationship, where minimal stiffness in the still curing resin/epoxy areas produces unpredictability in the results and allows the influence of gravity to be more significant, minimizing dimensionality. In any case, releasing pre-stress during the curing process means the material will solidify in its 3D position. This renders a greater amount of stiffness for the curved state.

Resultantly, to return the material to its initial flat state requires considerably more force than what was initially instilled in the pre-stressed textile. Introducing this variable relationship of curing time to post-forming allows for a multitude of forms to be generated from the exact same layup of materials. Each iteration, as a result, has quite different characteristics in geometry and structural behavior.

**POST-FORMING OF INTEGRATED TEXTILE HYBRID MATERIAL SYSTEMS**

Establishing the fundamental parameters and design methodologies for the post-forming process, a multi-layer prototype is developed to exhibit the various aspects of the fabrication process and behaviors of the integrated textile hybrid material logic. The prototype varies in composite stiffness, localized pre-stress and consolidation between layers. The flat-formed sheet is transformed into a spatial material structure, through the post-forming process, resulting in a material system with areas of full consolidation between all layers and a central strip delaminated from the pre-stressed textile (Figure 3).
The major steps of fabrication for the pTRC materials are:

1. pre-tensioning the elastic textile on a flat bed,
2. placing the textile(s),
3. applying masking layers, and finally
4. vacuuming the material assembly for consistent distribution of epoxy (Figure 6).

Initially, the pTRC samples were made by cutting the fabrics into custom shapes before the application of the resin. However, this produced great unpredictability due to the fabric stretching when the resin was applied. Ultimately, a portable frame is utilized for the layup of textiles which are not pre-cut. Rather the fabric patterns are masked using PETG between the layers of textile, as identified in step 3. The masking allows for distinguishing areas for epoxy impregnation and differentiating the number of textile layers in different composite areas.

To trigger the rebounding effect, the final steps are:

5. cutting away of layers of epoxy impregnated areas, as defined by the masking, with CNC knife-cutting, and
6. removing the masking sheets which releases the pre-tensioned textile and initiates the forming process.

MODES OF SIMULATION FOR TEXTILE AND COMPOSITE BEHAVIOR

With the design of textile hybrid systems, it has been shown that this can be accomplished across a range of design modes from experimentation with physical models, to exploration and analysis with computational simulation (Ahlquist et al. 2013). The methods of simulation split between particle-spring method and finite element analysis (FEA). The particle-spring methods offer rapid means for manipulating topologies and the behavior of tension and bending stiffness during the process of form-finding (Ahlquist et al 2014). This is a critical capacity when the complexities in material behavior increase. With a fixed topological model, FEA serves to give final description of the form where material properties and proper descriptions of force distribution can be employed.

The type of textile hybrid system posed in this research introduces stiffness in surface elements which have a differentiated thickness. At this stage, the research focuses on simulation of the post-forming process of the pTRC materials. Therefore, the concentration is on simulation of differentiated surface stiffness and its degree of influence to and by an integrated pre-stressed surface. Simulating stiffness in a linear element is geometrically straightforward. Though it has a material cross-section, if that cross-section is uniform, it can be modelled as a series of lines. As a surface, a mesh has to be utilized where the topology of the
meshing becomes critical. This is especially the case in the particle-spring model as it defines the axes at which the surface can buckle. While a triangulated mesh is used in these simulations, this requires further refinement so that the bending is not constrained to only the U, V and diagonal directions (Figure 7). Given the differentiated nature of the surface elements, it is necessary to rely upon physical material studies as the basic precedent (Figure 8).

**POST-FORMING COMPOSITE PROTOTYPES**

These initial prototypes studying integrated textile hybrid systems each examine a particular aspect of the structural material-inherent logic. The first series of studies, *Modulated Surface Deformations and Multi-Directional Voronoi Folding*, focus on varying the boundary conditions in material make-up (stiffness) and geometry (orientation to biases of pre-stress) to maximize the post-forming transformation from flat sheet to 3D form. The subsequent studies, *Differentiated Bi-stable Folding and Mechano-Graphical Aggregation*, look to find additional material behaviors beyond the embedded ductility from the textile hybrid system. In particular, these prototypes introduce aspects of multiple equilibrium states (bi-stability) and morphability through actuation.

**FORMING VARIED BOUNDARY CONDITIONS: MODULATED SURFACE DEFORMATIONS PROTOTYPE**

Central to this investigation is the relationship between the orientation of wood fibers as a natural composite material and the integrated pre-stressed textile, in order to achieve high degrees of surface modulation (Figure 9). The wood veneer is utilized as the primary agent for localized bending stiffness, to work in equilibrium with the tensioned textile. The materials utilized include a micro-thin wood veneer (1/64” in thickness) and a four-way stretch tricot knitted textile with 83 per cent polyester/17 per cent Spandex yarn.

Across a series of studies, the textile is variably pre-stressed, uni-axially or bi-axially, while the widths and layouts of the laser-cut veneer patterns are varied (Figure 10). In the bi-axial setup, the amount of tension in the textile is varied between the warp and weft directions in order to equalize the degree of stretch, or displacement, in the material. This provides an equal rebounding effect. A Birchwood veneer is used due to its specific high breaking strain with a low elastic modulus. Additional pliability is gained by laminating the wood veneer to the textile. This combination of materials and use of pre-stress exhibits the fundamental capacity of TRC material systems to produce highly articulated and extremely lightweight undulated surfaces from flat-formed sheets.
MULTI-DIRECTIONAL VORONOI FOLDING PROTOTYPE

This prototype explores the degree of separation (or delamination) between composite and pre-stressed textile layers, defined by interconnected cells (Figure 11). Foldability is studied by varying the flexibility of the composite formed areas between cells. The volumetric nature of the individual cell, expanding upon the initial Delaminated Morphologies Prototype, is generated by the relationship between stiffness of the open composite mesh (or webbing) and pre-stress of the integrated textile. This is studied through physical experiments and finite element analysis (Figure 12) to tune the material thickness and widths compared to the amount of tension in the pre-stressed textile. Material hierarchies are evident in the topology and steps of fabricating the material system (Figure 13). The fold-ability of the global form is achieved with the unbiased Voronoi-Delaunay pattern in the layout of cells and a secondary textile fused along isolated pathways within the larger Voronoi network. The pre-stress of this textile induces certain folds across the entire sheet, yet its elasticity allows for a multitude of reconfigurations (Figure 14).

RECONFIGURABLE TEXTILE HYBRID SYSTEMS: DIFFERENTIATED BI-STABLE FOLDING PROTOTYPE

This prototype explores folding with doubly-curved surfaces using the TRC forming methods. With the manipulation of the composite thickness based on number of textile layers, a bi-stable folding material system is achieved. Focusing on the bi-stable behavior, an individual component is comprised of two critical features: an arched fold located at approximately one-third of the overall length, and a straight fold that runs from one edge to the center of the arched fold (Figure 15). The interfacing area between these two surface features produces a doubly-curved transition zone. This resultant geometry is a key aspect for the flipping and stability of the bi-stable condition. When inflected at the right spot, the component flips from its folded state to a curved state. Further studies reinforce the necessity of the arched fold and the neighboring areas of double curvature to produce bi-stability (Figure 16).

Simulations using finite element analysis are examined to explore articulation in material composition and its effect in material forming and bi-stable behavior. In analyzing the FEM simulations, textural patterns are ascertained to inform surface deformations in a more subtle manner. These patterns are derived from studies of the principal bending moments of a single cell (Figure 17). A range of textural patterns are coalesced into a macro-structure of continuously connected components, exhibiting variation in localized bi-stable behavior (Figure 18). This describes a logic where the proximity between edges of the patterns defines a range of geometries from a fold to a gradually curving surface.

11 Hierarchies of the material system for the Multi-Dimensional Voronoi Folding Prototype: (1) cell boundary, (2) internal cell webbing, (3) pre-stressed textile surface, and (4) area between cells for folding

12 Studies with finite element analysis (FEA), in Sofistik, to calibrate relationships between textile pre-stress and composite stiffness in the cell boundary and internal cell webbing

13 Topology and phasing for the fabrication of the Multi-Dimensional Voronoi Folding Prototype, showing an additional forming process to laminate a pre-stressed textile across a range of cells within the Voronoi network
Multiple folded configurations accomplished by controlling the stiffness between cells and introducing a secondary pre-stressed textile.

Topology and features of a single bi-stable component, developed through the relationship of the straight spine to the moments of curved arch folding.

Variation of relationship between linear fold, arched fold and textile layers to determine ability for bi-stable behavior.

Translations between drawing, physical model, FEM simulation and analysis of bending moments to define final pattern.

Aggregation of differentiated bi-stable folding components, showing changes in the composite texture affecting the nature of the overall surface deformation.

MECHANO-GRAphICAL AGGREGATION PROTOTYPE

This prototype integrates shape-memory springs to actuate a multi-layered TRC material system. The complexity in material specification is increased by needing the composite and textile behavior to work in tune with the transformational force of the shape memory material (Figure 19). Physical and computational studies examine the additional parameters of additive reinforcements and actuation, along with textile types and number of textile layers. After a set of physical tests, the design factors of the individual three-legged cell are identified as (1) the ratio of the length to width of the leg, (2) the area of the center adjoining area for the three legs, and (3) definition of composite thickness in both areas.
With that logic, simulations are performed based on a prototypical component in Sofistik, with the primary variation between studies in the amount of area for the center region of the component (Figure 20). In varying the elastic modulus, a non-linear behavior is seen where a snap-through (inverted curvature) in the legs has occurred (Figure 21). To prevent such deformation, the narrower legs are reinforced with polyamide twisted ropes to increase the cross-section, pushing the “hinge” moment to the junction of the legs and the center area. The prototype consists of two mirrored pTRC materials that amplify each other’s deformation and produce volumetric spaces in between. To utilize the bending-active equilibrium and animate the interacting forces, the reinforced components are connected to their respective counterpart with Flexinol shape memory springs to temporarily suppress the pre-tensioned textile and actuate the material system’s topography (Figure 22).

CONCLUSION

Engaging pre-stressed textile reinforced composites as a material system significantly shifts the concept of a form- and bending-active structural logic. In previous research of textile hybrids, the goal was to deploy this logic at the moment in which separately manufactured materials textiles and composite rods were interconnected. In this research, such behavior is invested during the process of forming, yet also repeats aspects of the same form- and bending-active behavior in the fully materialized system. From a methodological perspective, materialization now embodies aspects of material behavior as a sub-routine of forming the whole of the material system. Specifically, this involves the rebounding process, in the relationship between composite curing and influence of the integrated pre-stressed textile. In this research, this served as a significant constraint where the degree of displacement is capped by the stretch in the pre-stressed textile.

Further research looks to compress the use of multiple textile layers into single differentiated knit construction (Figure 23). This leverages techniques available with flat-bed weft knitting. Varying knit density provides for a more refined control of composite stiffness, eliminating the need for a post-cutting process to remove layers of the epoxy impregnated textiles. 3D features can be constructed directly in the textile, as well as areas of high elasticity to serve as the means for post-forming. Examining the variation in yarn properties, textiles can be formed by intermixing yarns for composite stiffness, such as fiberglass or Kevlar, and ones for elasticity, such comingled polyester/elastin yarns. Designing at this level of detail is intended to provide a more intimate control over the post-forming process and, ultimately, the tailoring of the spatial and structural performance of the material system.
ACKNOWLEDGEMENTS
This research was developed with the students of the Master of Science in Material System program, with assistance from Assistant Professor Wes McGee and researcher Peter Halquist at the University of Michigan, Taubman College of Architecture and Urban Planning. Additional support was provided by the Research Through Making Grant (funded by the Taubman College of Architecture and Urban Planning) and the MCubed Program (funded by the University of Michigan).

REFERENCES


SEAN AHLQUIST is an Assistant Professor at the University of Michigan Taubman College of Architecture and Urban Planning. He is researching the topic of Material Computation and co-directing the Master of Science in Material Systems program. He is part of the Cluster in Computational Media and Interactive Systems which connects Architecture with the fields of Material Science, Computer Science, Art & Design and Music. Ahlquist’s research formulates computational design frameworks which place materiality as an a priori agent, focused on textile-based material systems, developing CNC knitting and composite-forming technologies.

ALI ASKARINEJAD is an architect and designer. He received his MArch and MSc with concentration in Material Systems degrees from the University of Michigan. Framed by the correlation of aesthetics and material studies, the focus of his recent work has been on the role of lexical and geometric languages in spatial configurations.

RIZKALLAH CHAARAOUI recently completed a Post-Professional Masters of Science in Architecture, with a concentration on Material Systems at the University of Michigan. In 2013, he was awarded the Fulbright Grant following the completion of a Bachelors and Masters of Architecture from the Lebanese Academy of Fine Arts, ALBA, in Beirut. In addition to his architectural background, Rizkallah strengthened his knowledge of design through various interior, lighting and furniture design projects, at a Beirut-based design practice.

AMMAR KALO is currently the Director of CAAD Labs in the Department of Architecture, Art, and Design at the American University of Sharjah. He recently received a Master of Science in Architecture with concentrations in Material Systems and Digital Technologies at the University of Michigan Taubman College of Architecture and Urban Planning. In 2014, he received the Kuka Young Potential Award at the RobArch 2014 conference. Prior to graduate school, Ammar gained experience working on international projects of various scales and typologies.

XIANG LIU graduated from the University of Michigan with the degrees from both the Master of Architecture and Master of Science in Material Systems programs. Xiang’s areas of interests include material research informed by computational design and fabrication technologies, and its atmospheric effects on light and sound. The work is often inspired and constructed from the cultural and geographic information of the site.

KAVAN SHAH received his MSc degree with concentration in Material Systems from the University of Michigan, where his focus of research was on textile and wood veneer composites. In the past, Shah has worked on various art installations in Mumbai, India, along with urban design collaborations with Isaac University in Barcelona and Urban Think Tank in Zurich.