A Case for Lace

Braided Textiles for Architectural Fabrication

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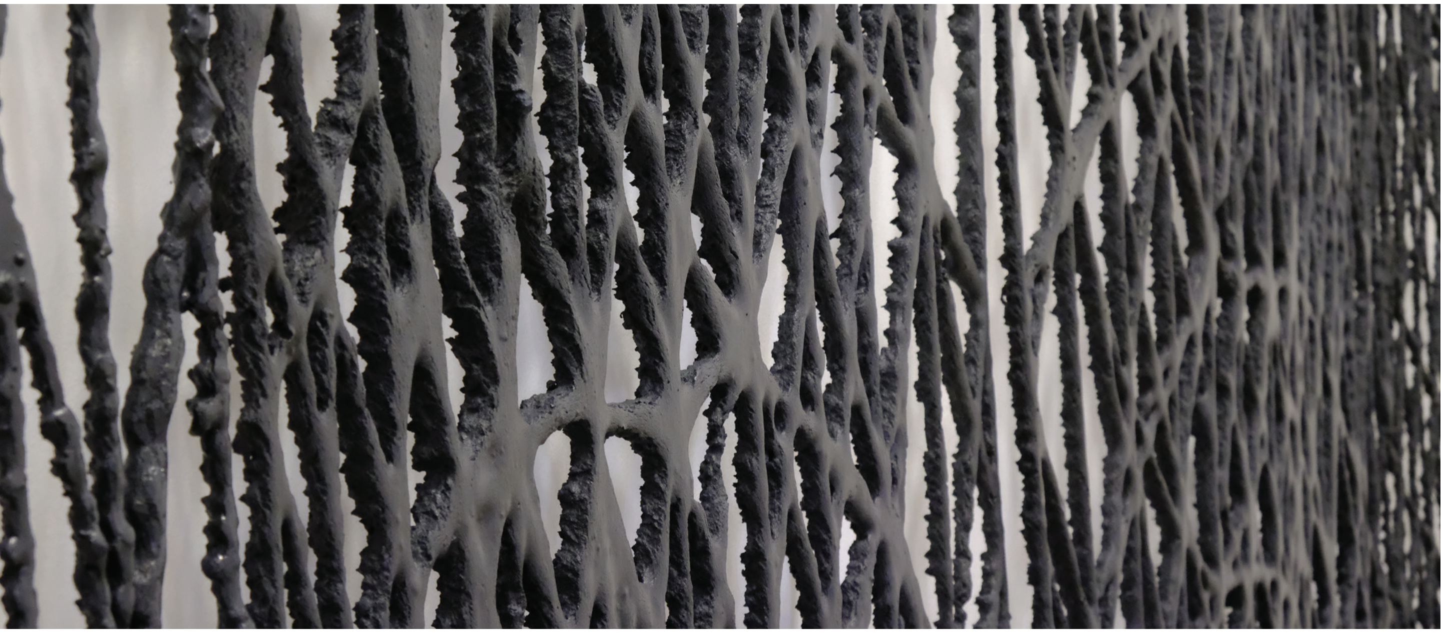


1 Detail photograph of *Concrete Tapestry.*

ABSTRACT

Textiles and architecture share a long, intertwined history from the earliest enclosures to contemporary high-tech tensile structures. In the Four Elements of Architecture, Gottfried Semper (2010) posited wickerwork and carpet enclosures to be the essential origins of architectural space. More recently, architectural designers are capitalizing on the characteristics of textiles that are difficult or impossible to reproduce with other material systems: textiles are pliable, scalable, and materially efficient.

As industrial knitting machines join robotic systems in architecture schools with fabrication-forward agendas, much of the recent developments in textile-based projects make use of knitting. In this paper, we propose an alternative textile technique, lacemaking, for architectural fabrication. We present a method for translating traditional lacemaking techniques to an architectural scale and explore its relative advantages over other textiles. In particular, we introduce bobbin lace and describe its steps both in traditional production and at an architectural scale. We use the unique properties of bobbin lace to form workflows for fabrication and computational analysis. An example of computational analysis demonstrates the ability to optimize lace-based designs towards particular labor objectives.

We discuss opportunities for automation and consider the broader implications of understanding a material system relative to the cost of labor to produce designs using it.

INTRODUCTION

Recently, textiles have enjoyed an increasingly prominent role in new directions for architectural fabrication. Designers recognize the unique material characteristics of textiles that are difficult to replicate with any other material system and have integrated textiles into increasingly complex assemblies. Among these characteristics, textiles permit control over material behavior through localized stitch selection (Ahlquist and Menges 2013), support structural integrity through embedded cross-sectional shaping and compositing of multiple layers (Popescu et al. 2018a, 2020), and are expressive through emotional and tactile feedback systems (Davis 2019; Ahlquist 2015).

Much of this recent work uses industrial knitting as the primary method of textile production and demonstrates methods for integrating textiles with architectural tools and workflows such as 3D modeling, simulation, and fabrication. By contrast, our research seeks to demonstrate how techniques from lacemaking, a lesser-used method of textile construction, offers distinct advantages in fabrication workflows with architectural tools.

We have identified three categories in the design and production of architectural textiles in which working with lace is advantageous: (1) fabrication workflow, (2) computational analysis, and (3) strategic material configuration. To support this claim, this paper presents original research in the form of two recent architectural installations that use lace as a primary tectonic as well as multiple investigations into the applications of the lace technique at an architectural scale.

BACKGROUND

A *textile* is a pliable material constructed from a network of intertwining fibers. There are many techniques to form a textile, including *weaving, knitting, crocheting*, and of interest to this paper, *braiding*. These categories of textile production are characterized by how the fibers interact. Braiding involves twisting two or more threads together. There has been some preliminary research into the computational modeling and fabrication of braided forms (Gmachl and Wingfield 2014; Marks 2017; Zwierzycki et al. 2017).

Lace is a braided textile characterized by its delicate, web-like form. In *bobbin lacemaking* each vertex of a pattern is located before braiding and pinned directly in place during production. Traditional bobbin lace is made in three phases: preparation, working, and finishing (Edkins 2017).

Preparation

Long fibers are first wound from each end onto pairs of handheld spools called bobbins (Fig. 2a). Pattern designs are transferred onto sturdy paper called *prickings*, which are perforated at the locations where pins will be secured into a backing cushion to hold braided threads in place. Bobbins are suspended in pairs from pins in the top of the pricking.

Working

After preparation, the lacemaker proceeds to work the lace by braiding two adjacent pairs of fibers together. There are only two valid operations for this braiding: the *cross* (Fig. 2b) and the *twist* (Fig. 2c). The cross consists of moving the right-hand thread of the left-hand pair over the left-hand thread of the right-hand pair. The twist consists of moving the right-hand threads of each pair over the left-hand threads of its own pair. A slight variation of the twist is occasionally used in which only one of the pairs is twisted (right-twist or left-twist).

During a braiding sequence, the lacemaker might also *pin* (Fig. 2d) between two pairs in order to tension individual fibers without affecting those nearby. The pin may occur in the middle of the braiding sequence (closed pin) or at the end of the sequence (open pin) and is inserted into the pricking pattern through a perforation in the pricking. Some grounds can be worked without pins, while other grounds require pins to secure the braids in place.

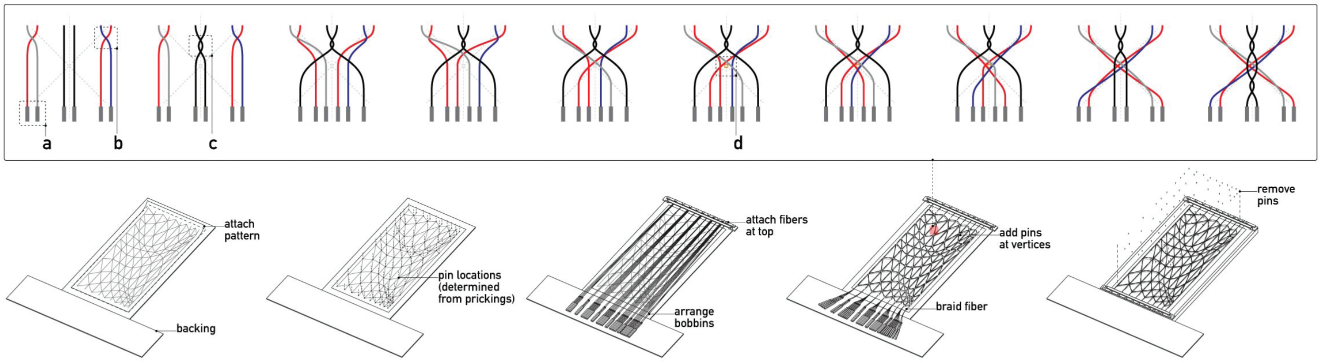
After a sequence is completed on four threads, a new set is selected and a sequence is applied. The new set may contain one of the previous pairs, but may also consist of two new pairs depending on the pattern and how the lace is worked. The cycle of selection and braiding continues until the pattern is completed.

Finishing

When a pattern is completed, the fibers are tied off or woven back into the design and the bobbins are cut from them. The pins are removed and the lace is complete.

METHOD

Our research adapts this traditional lacemaking workflow to an architectural scale. In the 3D modeling environment, this includes generating and evaluating patterns and sorting and outputting geometric information such as edges and vertices so it can be physically worked in the correct order. In the physical environment, our process translates the traditional tools of lacemaking, such as bobbins, pricking patterns, and pinning cushions, into larger-scale operations for architectural assembly that can be precisely represented by digital models. In doing so, we circumvent some of the fundamental challenges associated with knitting and weaving.



2 Process of forming a lace stitch with bobbins.

Fabrication Workflow

In a computational workflow typical for textile-based architectural fabrication with industrial knitting, geometry is initially modeled as surfaces (e.g., NURBS or mesh patches) and then converted to a stitch mesh subdivision for simulation and form finding (Popescu et al. 2018b). In a separate process, the 3D model must be converted into properly gauged stitch matrices for textile machines in a process analogous to vector-to-raster conversion (McCann et al. 2016; Narayanan et al. 2018). As a result, there can be an extensive process of developing reliable approximations between digital and physical models in architectural workflows (Sabin 2013; Sabin and Pranger 2018).

These challenges originate in a fundamental characteristic of knit and woven textiles: they are composed of aggregations of single stitches, which are individually unit-less and unpredictable, similar to digital pixels. The size of a basic unit of knitting—a single stitch—is difficult to estimate, since it is affected by numerous variables that can affect the length and geometry This results in complex methods necessary to estimate the size of each stitch (Ramgulam 2011). Physical dimensions are manipulated through adding or subtracting individual stitches, or by changing the operation of the machine to adjust the relative size of each individual loop. In the creation of three-dimensional textiles, this process reflects the contrasts between path-based information that exists in 3D models in comparison to two-dimensional rastering of stitches, where path-based shapes must be approximated by whole numbers of pixels (Lourie 1973).

Alternatively, braiding offers a method for physically constructing the textile from its literal representation in the digital modeling interface, which is not subject to the same challenges as knitting or weaving. Lace is directly constructed from a set of edges and vertices, and the digital representation is identical to the physical output and may be described by a mesh. 3D meshes can be used simultaneously for digital processes and physical fabrication without extensive geometric conversion.

Existing research examines a similar relationship between the production of complex form and traditional braiding techniques, showing how current computational tools for textile design are limited by matrix-based stitch control systems. Here, some work has also been done to develop methods of digitally generating braid structures that can cover complex surfaces, showing the possibility for textile production related to three-dimensional form (Győry 2016). In another vein of computational research related to braiding, computer scientists have developed a computational tool for generating geometric variety in braiding patterns, showing that stitch-level pattern control can exist for this textile production method as well (Irvine and Ruskey 2014). Traditional techniques show both complex three-dimensional form as well as spatial control of physical location of individual patterns. In particular, traditional bobbin lace allows intricate construction of detailed imagery along with physical integrity produced through intertwined fibers (Dillmont 1924). The proposed workflow explores braiding—influenced by traditional lacemaking techniques—as a textile production method that has potential for dimensional precision in textile components.

Braiding Workflow for Three-Dimensional Surfaces

Our three-dimensional lace workflow consists of three steps: first, a 3D digital model of a surface is converted to a fiber stitch pattern; second, the vertices from the pattern are output into instructions for a rudimentary “machine”; third, a physical object is constructed by hand using the three-dimensional information generated by the machine instructions.

In the first step, a "braidable" pattern of ordered lines is applied to a 3D surface. There are numerous existing patterns that could be used for this purpose, but the "eight-thread armure" pattern is selected because of the simple fiber intersections at vertices, enabling a first step of integrating the traditional technique with a new process (Fig. 3).

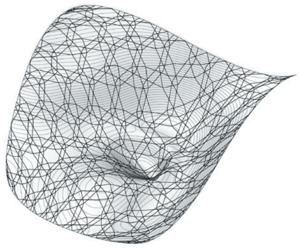
The workflow allows the input of a user-generated three-dimensional surface to which a braiding pattern is applied. There is also a series of user inputs that allow for selection of density and proportion of the textile patterning. The pattern is visualized as a set of continuous strands that are to be physically intertwined during the production process. From these, a set of X, Y, and Z coordinates are located and assigned an order according to the process by which the braiding technique will be applied to each fiber. This information is then separated into coordinates in the X-Y plane, and a set of Z axis positions (Fig. 4).

The coordinates in the X-Y plane are used to generate a 2D pattern that records both the order and physical location of braided vertices. The sequence of vertices represents the order in which each fiber vertex is physically intersected and fixed in place by its Z axis pin. For the pattern used here, the vertices are constructed in sets of four, which are then organized into rows that are fabricated sequentially (Fig. 5).

In the Z axis, there are two pieces of information that transfer from the digital model to the device for fabrication: first, the height of each vertex is used to determine the location of a hook on each pin; second, the curvature of the input surface is analyzed to generate a selection of hook detail. Depending on the location of the vertex within the curvature of the surface, the hook will either tension the fiber upwards or work to fix it down. The Z axis dimensions, along with the selection of hook detail, are output to fabrication drawings for a set of unique pins that match the height of each vertex location in the braiding pattern (Fig. 6).

The method of Z axis construction reflects the most significant difference between the proposed method and the traditional method of producing the textile; traditional techniques for producing three-dimensional lace objects typically use a solid three-dimensional form with a generic pin (Fig. 7).

In Figure 8, a series of small-scale studies show that edge-and-vertex patterning of a doubly curved surface can be fabricated as a continuous linear network by braiding fibers. The physical models are constructed from ordered vertices directly outputted from the digital model and that correspond to the assembly of braided fibers.



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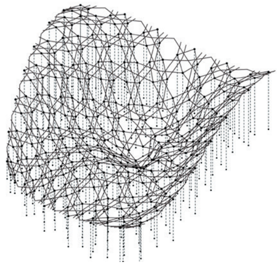

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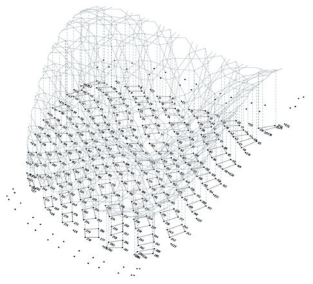

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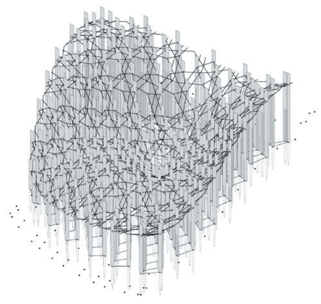

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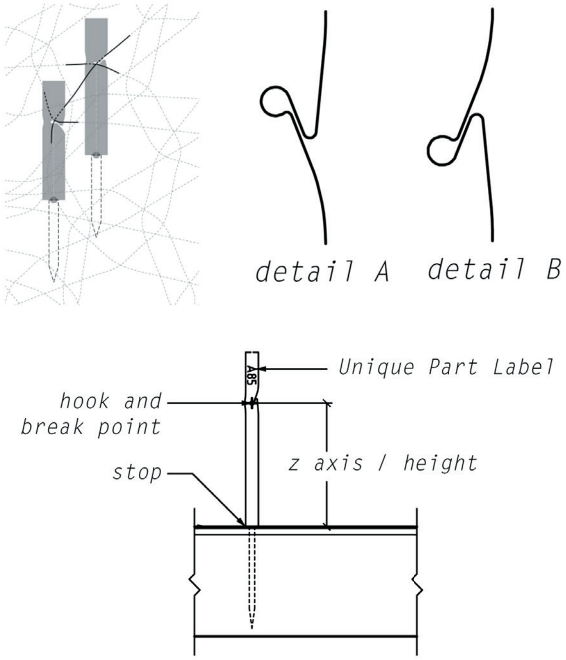
3 Braiding pattern applied to curved surface.

4 Pattern projected to X-Y plane.

5 Ordered set of X-Y vertices for braiding.

6 Z axis pin parts match surface curvature.



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7 Curvature-sensitive pin detail registers Z axis position of lace.

Translation to Architectural Scale

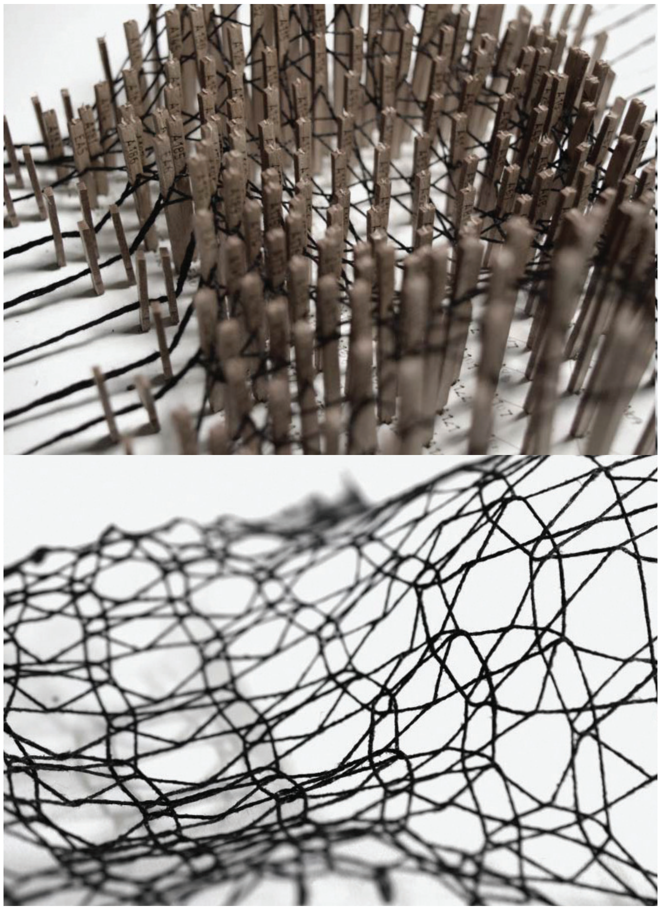
The project *HEDGE* (Fig. 9) demonstrates that lacemaking for architectural fabrication permits a direct correlation between digital modeling and textile fabrication at a large scale. *HEDGE* is a braided carbon fiber screen adorned with 2,000 pounds of plastic parts that are the repurposed byproducts of a local industrial process. The installation creates a synthetic spatial "vegetation" in the exterior courtyard of the Contemporary Art Museum St. Louis, demonstrating a hybrid of digital and analog craft processes that capitalizes on the efficiency of digital design dexterity of handcrafted work. The plastic parts are suspended by an ultra-light netting of resin-impregnated carbon fiber strands. The technique offers a method for fabricating a high-tensile-strength armature without knots or fasteners. The digitally optimized morphing diagrid responds dimensionally to the site context, desired visual densities, and structural considerations; the pattern is manually traced onto plywood panels and hand-braided using bobbins wound with carbon fiber. Thirty hand-braided panels arranged in two rows covered an area of approximately 38 feet by 10.5 feet and were designed with a parametric model.

Computational Analysis of Embodied Labor and Structural Performance

The flexibility and large design space associated with bobbin lacemaking challenges the designer to balance competing forces: pattern density vs. labor cost, load density vs. structural performance, and the interconnected nature of any such decisions. The precise digital representation of textile vertices permits the application of optimization tools for managing these trade-offs.

Historically, great value has been attributed to lace based on the fact that it is labor intensive, and thus rare and exclusive. Working towards an architectural scale only compounds this problem.

Producing lace involves several labor-intensive steps. At the same time, the geometry of the lace is encoded with information about the labor, or effort, required to produce it. For example, adding additional columns to a lace pattern will require more effort than adding the same amount of rows because it requires more effort to prepare and mount the bobbins needed to produce the extra width whereas extra length is achieved with the same number of bobbins. Even more effort is required to introduce subdivision patterns to the lace, again requiring extra bobbins for the extra threads, but also requiring extra cognitive effort to manage the additional threads as they propagate through the design.



8 Small-scale study of fabrication workflow for a doubly curved lace surface.

In a load-bearing application of lace such as *HEDGE*, the trade-off between the effort required to make the lace and its structural performance can be explored. Here, an analytical workflow is presented that optimizes the shape of the lace by reducing the highest contribution to labor—subdivision—only where it will reduce the overall stress in the structure. The specificity in steps to make lace, coupled with a mesh representation, allows designers to optimize labor resources relative to performance criteria.

Computational Model

A computational model needs to consider the following labor-important variables: the number of vertices in the design and the number of bobbins required for pattern. Additional labor includes the embodied cognition of managing the complexity of deploying bobbins and managing them as they move through the pattern. The following equation summarizes the embodied labor of particular design:

$$L=V+B$$

9 *HEDGE* installation in the exterior courtyard of Contemporary Art Museum St. Louis, showing the panel elevation diagram, fabrication armature, and full-scale installation.

where *L* is the total embodied labor, V is the embodied labor contributed from vertices, and B is the embodied labor contributed from bobbins.

If visual variety achieved by varying density of a pattern is the strength of bobbin lacemaking, it is also the challenge for the designer balancing competing forces of labor with visual complexity. Density may be introduced to a pattern by four methods, or any combination thereof:

1. Bunching vertices together
2. Adding rows
3. Adding columns
4. Local subdivisions

Each strategy is associated with a different cost of embodied labor. Topology-preserving translation of vertices adds no extra labor because the vertex count and required amount of bobbins are unchanged. Adding rows only adds vertices, as bobbins are mounted at the top of each column, irrespective of how many rows are in the pattern. Adding columns, however, will increase the vertex count and the required number of bobbins. Finally, local subdivisions add both vertices and bobbins, as extra bobbins are required to be mounted at the top of any column that contains a subdivision. The net changes in required vertex labor (V) and bobbin labor (B) under the above conditions is summarized below:

1. $\Delta V=0;\Delta B=0$
2. $\Delta V>0;\Delta B=0$
3. $\Delta V>0;\Delta B>0$
4. $\Delta V>0;\Delta B>>0$

In structural bobbin lace, as in *HEDGE*, the designer might also introduce applied loads to vertices, treating the lace as a lattice on which to suspend other elements contributing to visual density.

Density in structural bobbin lace is achieved by a variety of methods and in response to a variety of factors. A designer must balance these considerations together in order to make the most of materials and labor. A computational model in the service of structural bobbin lace will address the following questions:

a. How dense is the pattern overall?
b. Where are the vertices located?
c. Is subdivision allowed?
d. What visual effect will adding external loads have?
e. What is the structural effect of the combined density methods?
f. Can these cause-and-effect relationships be visualized to generate a catalogue of design options?

Answering these questions requires the following corresponding parameters, subroutines, and outputs:

a. Row count, Column count;
b. Subroutine for moving vertices without breaking topology;
c. Domain(s) where subdivision is allowed;
d. Subroutine for adding external loads;

e. Subroutine for structural analysis; and
f. Visualization of all criteria

With the designer's questions reformulated or addressed as series of parameters, subroutines, and outputs, a hybrid computational and human workflow model is outlined below:

1. A parametric model in *Grasshopper* will initiate a base line Torchon ground tiling of a rectangular surface in the XZ plane. The density of the initial grid will be controlled by the u and v density of tiling, and corresponding to density methods (2) and (3), the rows and columns of the pattern respectively (Rutten 2018).
2. The designer decides if B, embodied bobbin labor, is sufficiently low (e.g., requiring a quantity of bobbins that is acceptable or available)
3. The designer chooses or generates a grayscale image that corresponds to desired density through method (1), "bunching."
4. The grayscale image locating areas with greater desired density is used with *Kangaroo3D* (Piker 2017) to shorten mesh edges near corresponding values of 0 (black) and to be unaffected by values of 255 (white).
5. The designer chooses or generates a grayscale image that corresponds to the distribution of load and sets an upper and lower limit of allowable point loads.
6. The grayscale image locating load distribution is used with *Karamba3D* (Preisinger 2013) and assigns the upper domain value of allowable loads to vertices with sample values of 0 and the lower domain value to vertices with sample values of 255.
7. The system is modeled with supports at the vertices coincident with the top edge of the initial rectangle from step 1 and load forces pointing down in the z axis.
8. The designer sets allowable domain(s) for subdivision. For example, if the loading image from step 5 contains one contiguous region of load density, the designer may choose to search the full domain. Alternatively, if the loading image contains three separate areas of density, the designer may choose to divide the full domain into three discrete zones for subdivision search.
9. *Goat* (Rechenraum GmbH 2016) searches the domain(s) of allowable subdivision to minimize $\sum_i |F_i| L_i$, a value proportional to structural weight and an output from *Karamba*'s structural analysis.
10. The final design is visually inspected and analyzed for total number of vertices and total number of bobbins, including those contributed from subdivision, and entered into a design catalogue for comparison.

From the outline above, the manual inputs and computational optimization variables and objective may be summarized as follows:

Inputs:

Number of rows
Number of columns
Image describing bunching of vertices
Image describing loading of vertices
Number of discrete, contiguous domain(s) for subdivision

Variables:

X_1^n: Lower boundary in domain *n*
X_2^n: Upper boundary in domain *n*

Objective:

Minimize $\sum_i |F_i| L_i$

Figure 10 shows the workflow described in steps 1–10 above.

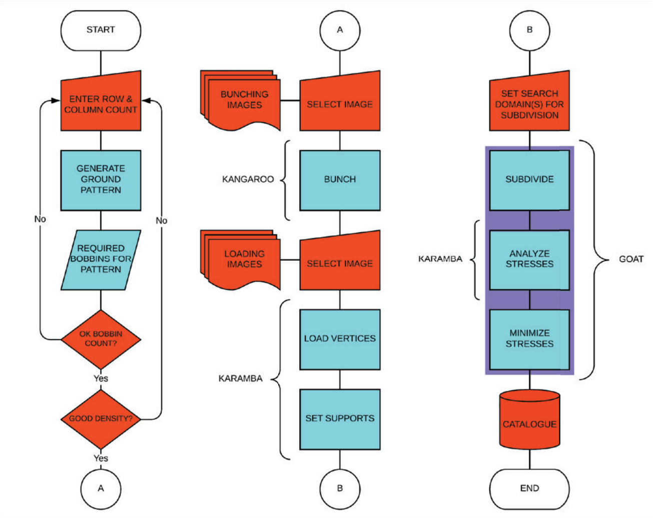
The method described here does not use optimization algorithms to minimize V or B directly, but rather uses structural analysis to generate subdivisions, with the highest contribution of embodied labor, only where it is structurally effective given the designer inputs. This solution gives the density methods with lower embodied labor priority in configuring the final output. The designer can produce a catalogue of results and decide which will best be suited for production.

A small catalogue of designs was created to test the efficacy of the method described above. The row count and column count was kept constant at 20 and 25, respectively, and a bank of grayscale images was created and used for the image sampling routines (Fig. 3). A selection from the catalogue is shown in Figure 12.

Strategic Material Configuration

Lace permits a wide spectrum of material characteristics. Other textiles almost exclusively act as membranes in tension (à la Frei Otto) rather than finite elements in either tension or compression. While similar polygonal shapes can be cut by CNC, there are two undesirable costs to that method: (1) material waste between the linear elements and (2) inaccessible high-performance composite material palettes.

In the project *Concrete Tapestry* (Figs. 1, 13), we applied a coating of concrete to four large, laced panels approximately 3' x 7' that were similarly prepared as in *HEDGE*, but introduced localized subdivisions within the lace to give greater density, and structural integrity, in the self-supporting panels.



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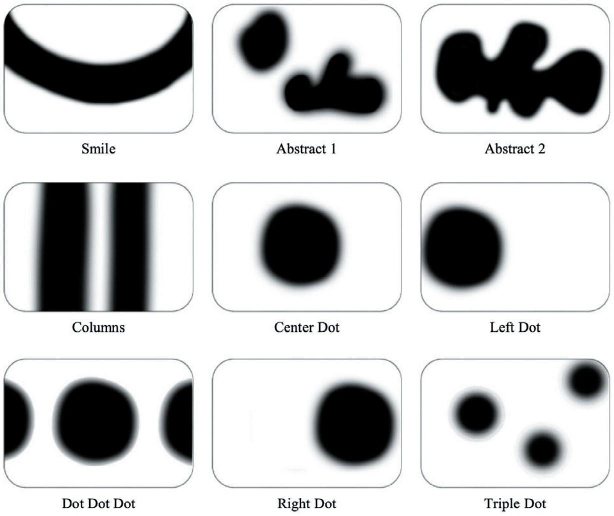

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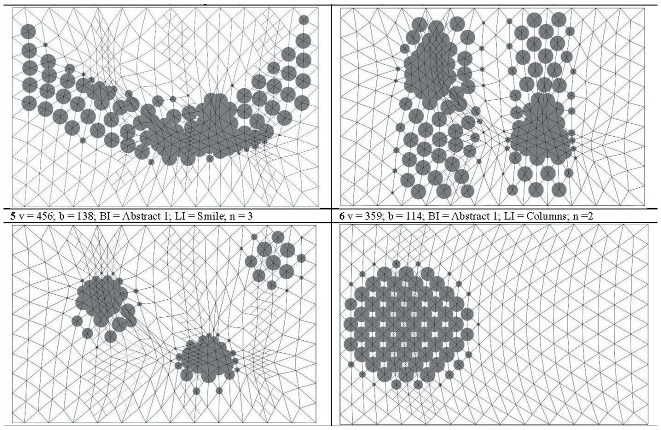

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10 Flowchart showing a *Grasshopper* workflow with human interaction (red) and computational processes (blue) to iteratively minimize labor (purple).

11 Selection of images controlling lace bunching and load density in optimization routine.

12 Selected designs from the optimization. Note that subdivision, the most labor-intensive process, only occurs near the applied loads.

At various stages in the fabrication process, the lace pattern enables the panels to perform in various roles: in tension during the braiding, coating, and curing stages, and predominantly in compression while cured and displayed.

DISCUSSION

We have shown that lace has certain advantageous properties when using textiles at an architectural scale. While not intended to replace applications where high-density or sheet-like textiles are preferred, and for which it would be hard to justify the labor-intensive process of making lace relative to established industrial processes, specific cases where there is a desire for large cellular spacing or linear networks of varying density support the choice of lace within the field of architectural textiles.

This body of work can be understood as the foundation for multiple modes of exploration. Now that we have identified the manual tools and computational steps for producing architectural lace, we can move towards automating parts of this process such as placing the pins in precise and customizable locations. This trajectory can lead to systems capable of generating machine instructions for textile and nontextile parts from the same 3D model using the same coordinate information. Ultimately, this body of research could develop towards applications in mainstream construction in which quality, consistency, and economy are prerequisites for widespread adoption.

Another way to continue this work is to focus on extending the methodologies of labor optimization to other material systems and to further develop a computational understanding of design criteria relative to labor consequences. Lace has provided an opportunity to study this interplay of constraints because the required labor to make it is directly related to its form and process of making. However, this line of thinking can extend to other methods of designing and making.

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HEDGE
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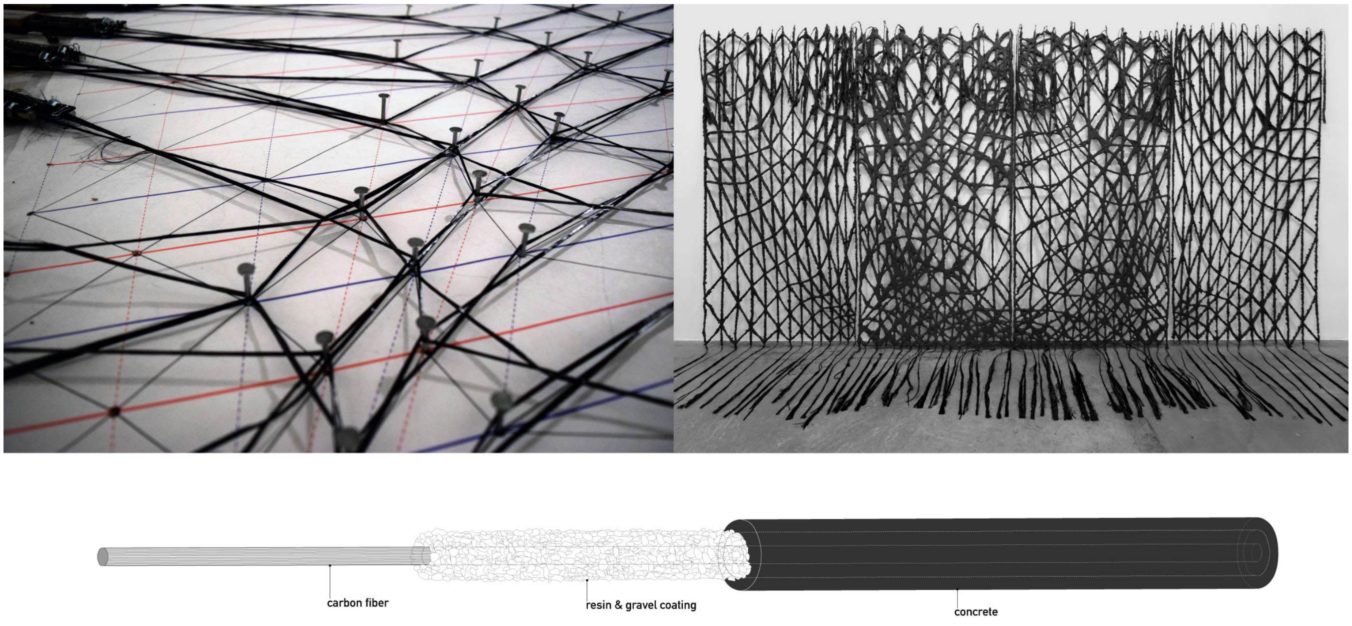
PROJECT TEAM: Evan Bobrow, Marija Draškić, Yuchen Song, Michael Zhou
FABRICATION ASSISTANTS: Sam Bell-Hart, Finnegan Roy-Nyline, Greg Smolkovich
WITH SUPPORT FROM: PolyOne



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13 Fabrication process, coatings diagram, and final installation of *Concrete Tapestry.*

Concrete Tapestry
DESIGN: Lavender Tessmer, Nathaniel Elberfeld, Alexandra Waller
FABRICATION ASSISTANT: Sam Bell-Hart
WITH SUPPORT FROM: Regional Arts Commission of St. Louis

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IMAGE CREDITS

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