Large-Scale Lightweight Transformable Structures

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1 Transformable Meeting Spaces in use.

ABSTRACT

This paper presents strategies for the creation of large-scale transformable structures. In particular we work to leverage material properties and novel construction techniques to induce transformation. We employ flexible biaxial braided geometries to create interconnected large-scale textile surfaces. These braided networks distribute load forces via their internal friction, allowing for uniform structural transformation without the need for complicated mechanical linkages or electromechanical actuation. The ultimate range of these structures has been simulated with computational tools and correlated with physical load testing. We present various applications and configurations of these transforming structures that demonstrate their utility and a new attitude toward the creation of lightweight morphable structures.

INTRODUCTION

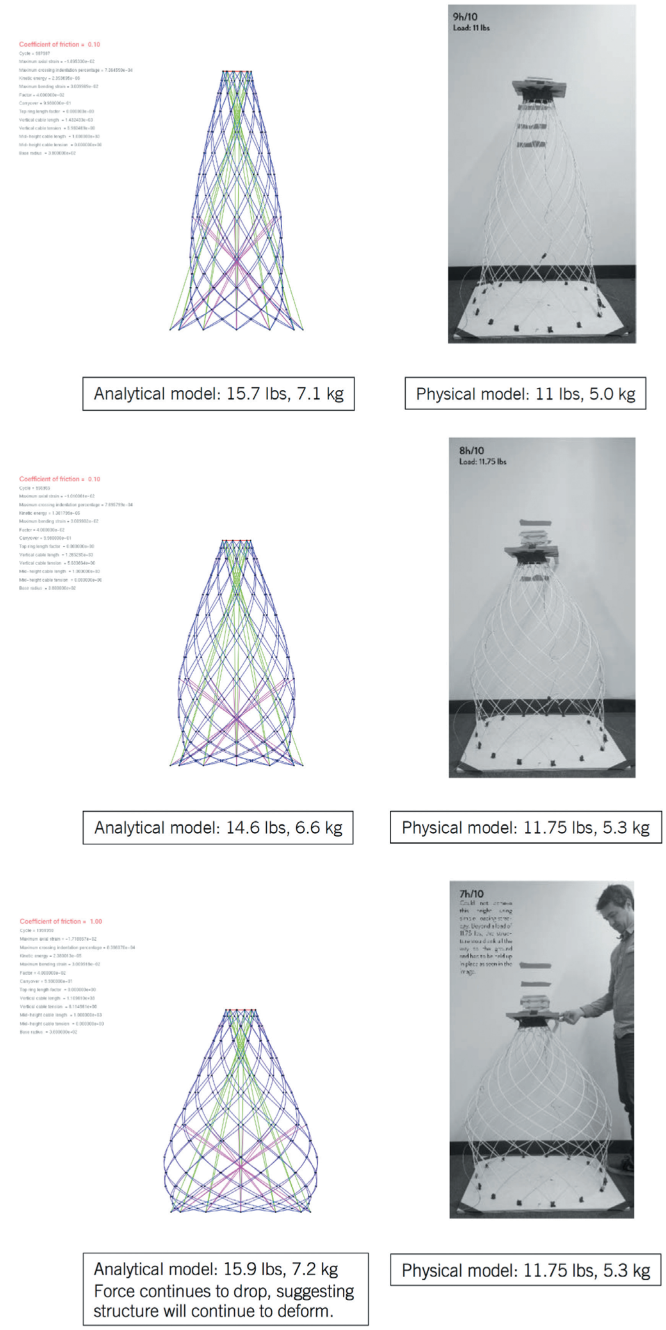
In this paper we present research on lightweight transformable architectures through biaxial braiding and minimal surface construction. These structures are able to transform locally and globally through the bending and sliding of the braided members without relying on electromechanical means. This approach stems from the blending of two perspectives. The first is the aim to build lightweight, quickly deployable structures; the second is to develop transformable and adaptive spaces. This research has focused on the development of large-scale textile-like structures that can form both structural and spatial volumes but can also transform with minimal external forces. In our aim to unify the insight of lightweight form-finding techniques with morphable structural systems, we have developed several braided structures at increasingly larger scales and demonstrated their utility in various applications.

BACKGROUND

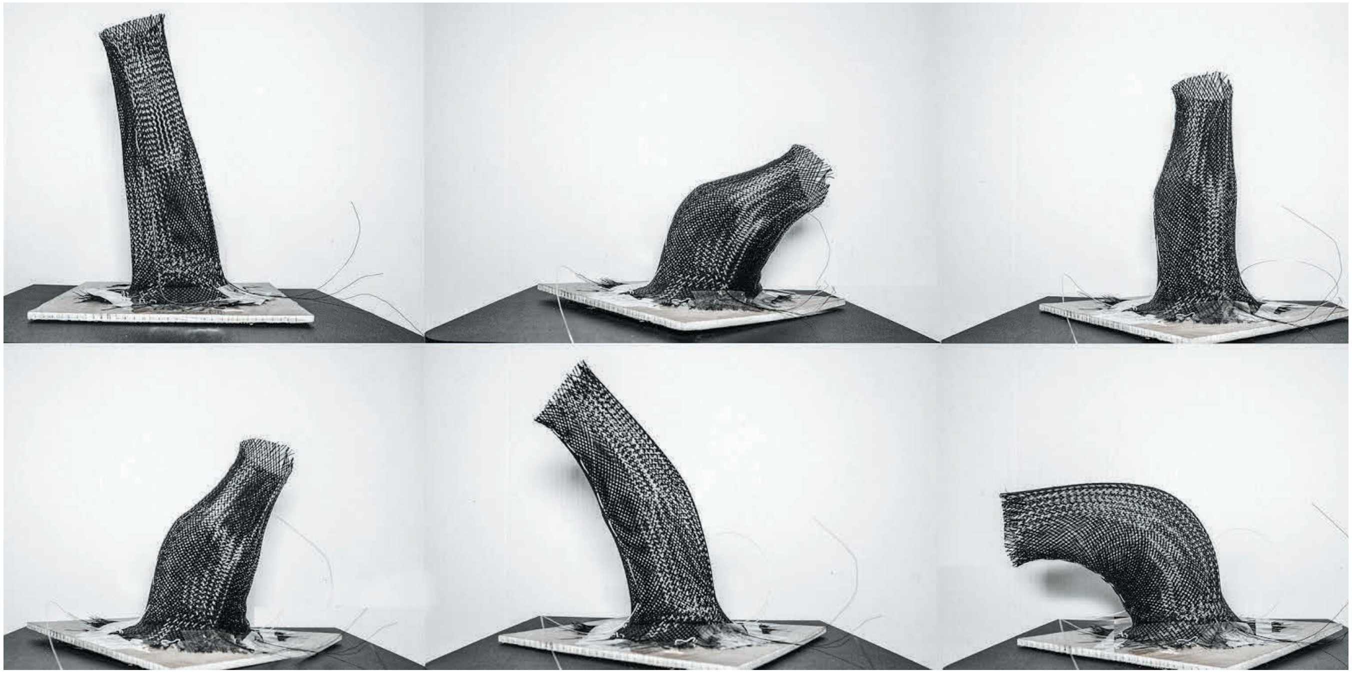
In 1968, a large retractable canopy, designed by Frei Otto, was erected to cover the open air theatre at the 12th-century abbey ruins in Bad Herzfeld in West Germany. Regulation stipulated that the design should neither damage the historical structure nor interfere with the romantic nostalgia of the location. Thin cables running across the open roof of the abbey supported the tensile "soap-bubble" membrane canopy. When not in use, it could be retracted and gathered-up by special trolleys running along the cables (Otto 2005). This canopy continues to embody the possibilities of lightweight, modular, and transformable design. However, when these tensile structures were made to transform, they surrendered their structural properties, lost their rigidity, and their minimal surface geometries when crumpled into a secondary state. Tensile structures often transform by changing states from an open deployed state to a folded/crumpled packed state, rather than transforming into multiple functional and structural conditions. The two states of transformation of the canopy in Bad Herzfeld perform structurally dissimilar tasks.

Other types of architectural transformation, like Chuck Hoberman's iconic Transforming Sphere and subsequent larger-scale work, exhibit topological and structural continuity throughout their transformation. However, these structures require mechanical linkages and eliminate the form-finding techniques and lightweight minimal surfaces of tensile systems (Hoberman and McQuaid 1994).

The current structural paradigm in precision robotics and large-scale architectural transformation is exemplified by complex mechanical transformations. These systems often rely on heavy electromechanical, pneumatic, or hydraulic mechanisms with power requirements, added cost, weight, and complexity. Our aim is to reduce this structural complexity with lightweight minimal surfaces and eliminate the reliance on complex mechanisms or power requirements for large-scale transformation.



2 Computational analysis of biaxial braided structures validated against empirical testing of the five-foot model.



3 Small-scale testing of biaxial braid transformation.

LIGHTWEIGHT TRANSFORMABLE STRUCTURES

By leveraging the inherent properties of biaxial braided structures, we have been able to produce large surface geometries that maintain their structure throughout transformation. Much like a Chinese finger trap, biaxial braiding employs two sets of strands braided into a regular grid. Although free to slide along each other, the strands composing the braid maintain their interwoven relationships even while pivoting or sliding. Relative sliding is resisted by the friction force between one member pushing on another, distributing forces evenly throughout the structure. The range and possible configurations of this system emerge from its geometry, material properties (friction and stiffness etc.), and braided construction pattern. As a result, these biaxial structures have the freedom to arbitrarily transform while maintaining their structure and strength.

We developed a series of braided cylindrical forms that can be constructed from flexible fiberglass rods or tubes. Applying force to the open edges of a cylinder widens its form. Compressing the sides of the cylinder lengthens its form. By constraining the diameter of the structure at certain points, limiting the ability of the rods to slide along one another, or anchoring the structure to a stable surface, it is able to assume many different forms. This is all done without the need to specify the location of every member or node within the structure. Internal friction transfers force from one fiberglass rod to its neighbors, allowing the braid to act as a single unit without the need for mechanical linkages (Figure 3).

With given constraints to the braid, the ranges of transformation can be determined through simulation and physical testing, a process that this paper will demonstrate. With these tools, the designer is able to predict the movement of a given structure.

The biaxial braid is just one example of a structural system that exemplifies our attitude toward designing large-scale lightweight spatial transformations. To push this even further towards lightweight systems, we developed an alternative approach, replacing the composite members with a 3D textile system that forms a continuous interconnected structure that is not bound by a cylindrical form. Like the biaxial braided system, the Transforming Screen project, a 54-foot morphable partition, is suited to particular applications that require lightweight and large-scale transforming structures in linear or non-closed geometries. This textile-based system also minimizes the construction complexity of braiding large structures.

Together these approaches contribute to a repertoire of self-transforming large-scale structures that propose an alternative approach to the current electromechanical, hydraulic, or pneumatic paradigms of kinetic architectural structures and robotics. This research also advances the form-finding possibilities of a material system by exploring physical and geometric transformations rather than static structures. By changing our attitude toward materials, traditionally seen as static and mechanically connected, we can now ask materials to self adjust and spatially transform.

SYSTEMS OF TRANSFORMATION

BIAXIAL BRAID

Biaxial braiding is one technique used for creating material transformations. The end of every strand is joined with another strand running in the opposite direction. With no loose ends, this braided structure is self contained, unable to unravel, and assumes a circular shape. The tightness of the braid is defined by the number of strands, where each individual strand is braided past a given number of members constituting the total structure. The stability of the structure is determined by this tightness—the number of rods in the braid and the number of over-under braided sequences in total—as well as the stiffness of the material and the friction coefficient. The ultimate range of transformation is also limited by this tightness and stiffness of the material. Ultimately, it is the friction applied from one member to its neighbor that transfers transformational and stabilizing forces.

These biaxial braids must be braided tight enough to support themselves with internal friction. If each strand passes by only two perpendicular strands, it will likely fail to have the necessary internal friction to stand on its own. Inversely, if this structure is interwoven too tightly, the internal friction will prevent it from transforming. Furthermore, the back and forth weaving of these strands may push the strands past their elastic limit. As the biaxial braid approaches its upper limit of tightness, the kinetic range of the structure diminishes. In the design of these biaxial braid structures, this tightness in relationship to the length, diameter, surface finish, and elasticity of the strand must be considered for the particular application of the given structure. For example, a structure standing in compression must be stiffer than a braid in tension to resist self-weight and buckling.

MATERIALS

Our braided structures are constructed primarily from FRP (fiberglass-reinforced polyester) rods and tubes. End connectors are epoxied to the ends of each rod, where they can be joined with simple bolts or shackles depending on the rigging system, mounting detail, or added constraints needed. The ends of these rods are allowed to freely pivot in relation to their neighbors. FRP provides a high tensile strength while remaining very flexible and lightweight, and resists plastic deformation. FRP rods are able to remain bent for long periods of time without permanently deforming. This allows for very consistent transformation throughout the life of the structure. To its disadvantage, FRP is prone to abrasive wear. Since friction is the means by which force propagates throughout the entire structure, it is impossible to avoid wear entirely. The tightness of the internal braid must be minimized to avoid premature wearing of the rods. Similarly, the density of the braid cannot be too large or the rods could snap due to its bending around the thickness of the neighboring rod. The need to keep the bend radius of the strands below their maximum threshold limits the possible height of the structure. In the construction of large-scale structures, hollow tubes were used to reduce the weight while maintaining the stiffness.

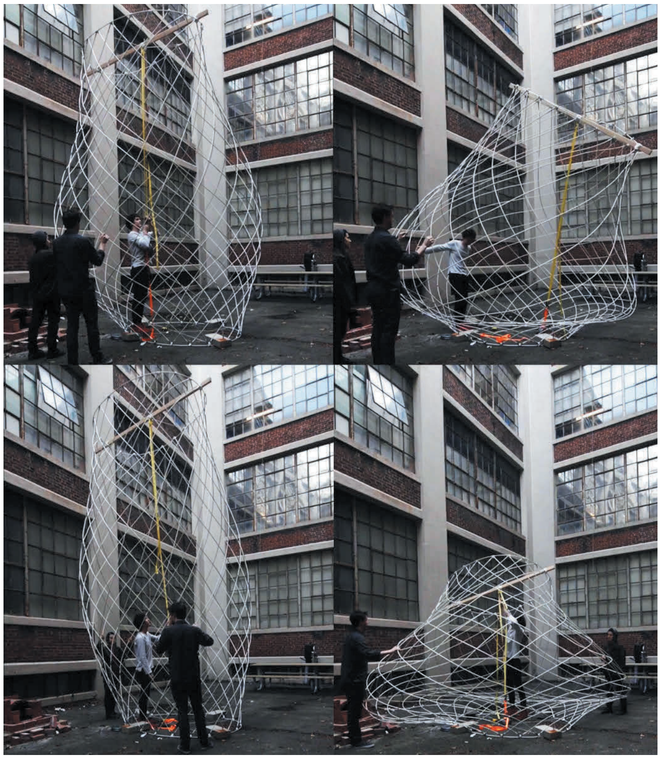
CONSTRAINTS

The full range of possible motion of the structure is only achievable by constraining portions of the braid's internal movement. Inducing resistance within selected parts of the structure allows force to pass through the braid in different ways, resulting in new transformational possibilities. Constraints can be used to limit or specify the type of motion desired from the system.

The application of pivoting connectors between two crossed rods keeps them from sliding along each other at a particular point. This limits the structure's ability to move asymmetrically above and below this node. These clamps help resist buckling when the members are working in compression by reducing their effective length. These joints can also serve as a point from which forces can be applied to the structure to induce transformation. Due to possible slenderness of these structures, they could buckle under self-weight if only supported from below. To avoid this the buckling load of a single member should be greater than the total weight of the member itself. The buckling load is governed by the effective length between restraints. Friction through sliding joints provides temporary resistance to buckling but the joints relax over time. The buckling length is therefore the distance between pinned supports. A balance is therefore required between member stiffness and the number of pinned supports.

Depending on how the structure is anchored, the diameter of either end is often fixed at a particular global diameter. This is done by bolting the ends of the rods to a solid surface such as the ground, or running a fixed ring of metal or fiberglass around the exposed diameter, fixing the rod ends at a particular size. Both ends of the structure can be constrained at particular diameters and this can be done at identical or different diameters. By setting the two ends at different diameters, the natural resting position of the structure becomes conical. These rings greatly increase stability and the ease by which one applies force to the biaxial braid. By merely pulling or pushing this ring, every rod is simultaneously affected.

Rigging studies were first prototyped using monofilament line. Initial tests showed how the structure could be transformed by pulling down on the braid from a single point at the top through a screw-eye at the base. Subsequently, a slip knot approach was tested to reduce the top diameter of the braid (Figure 3). The rigging of small biaxial prototypes was further developed with 1/16′′ diameter aircraft cable. These aircraft cable rigging lines



4 Twenty-foot prototype being tested with various loads to show deformation and verify the simulation.

were attached to the top nodes of the braid or to a top ring on some of the variants. Attachments to the structure were made by looping the cable around the fiberglass rods and securing them with oval compression fittings. Two approaches were used in routing the cables on the prototype structures. The first method was to weave the cables through the biaxial braid in a shortest-line path to the ground. However, this introduces unnecessary friction between the cable and the rods. The second method was to run the cables down the surface of the braid and through a screw-eye at the base of the structure. Loading studies that were conducted on a twenty-foot tower prototype by attaching a rigid member across the top diameter of the tower, then applying load to the midpoint of the span by attaching increments of ten-pound weights via nylon webbing (Figure 4).

ANALYSIS

The behavior of the biaxial braid has been modeled using a custom computational tool, since existing structural analysis software could not account for the following features:

- Structures relying on a braid for rigidity
- Curved structural elements sliding past each other
- Large-scale deformations: normally structural deflections are barely noticeable
- Motion: varying cable lengths manipulate the motion of the structure. The motion depends on the distortion of the mesh.

A custom analytical script was therefore developed by Atelier One in collaboration with Chris Williams of Bath University. In the script, each rod is split into a series of shorter elements of varying length. The rod-bending stiffness is then modeled using a three-point bending formula (Adriaenssens 2000). The method allows for the calculation of contact forces and for the rods to be split into varying lengths, thus allowing contact points to move along the length of the rods (i.e., slide). Fixed positions on different rods can be locked together to model pinned connections. A dynamic relaxation method is then used to find the equilibrium form. This includes damping to prevent the model from becoming unstable.

The script successfully accounted for all of the complexities listed above. The analytical model correctly predicts the manipulated shapes of the braid and gives a good estimate of the structural deflections under load. The testing of physical models demonstrated that the analytical script provided a good approximation of the actual behavior (Figure 2). The script could be subsequently used to test the possible forms of the structure without the need for physical testing.

RESULTS & IMPLEMENTATION

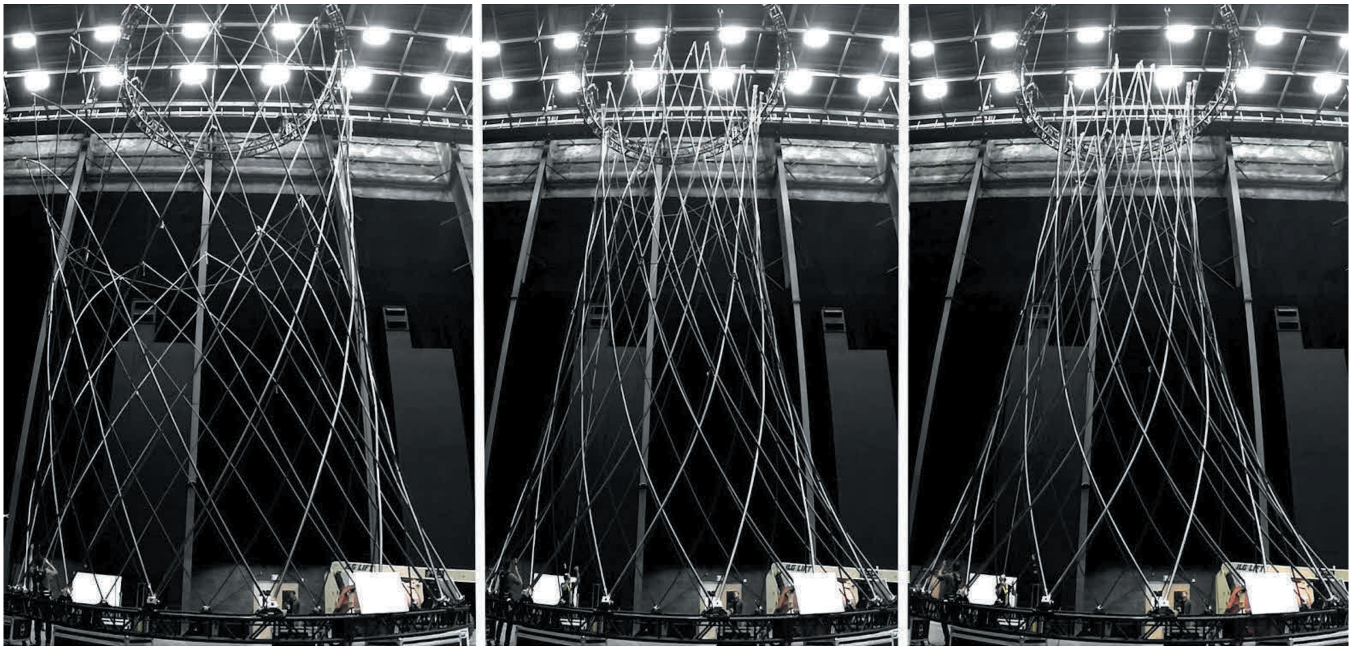
We have developed several biaxial braided structures at various scales with different rigging configurations and mounting strategies. Our experiments have tested possible use-cases, cladding strategies, spatial qualities, and user interactions, in addition to fundamental research into the system's structural qualities and transformative possibilities. For the purpose of creating human-scale spatial transformations, we have made several tests that exhibit possible approaches to cladding these gridded structures. We have primarily explored two possible structural configurations: ground mounted, and ceiling mounted. These two mounting strategies impact the natural resting state of the structure, thereby affect the rigging system, and finally dictating the possible application of the structure.

GROUND-MOUNTED STRUCTURES

Ground-mounted tower structures are mounted to the ground, where the bottom edge is locked into a fixed diameter. In this position, the structure must support its own weight in addition to the forces applied by rigging and wind load. As such, a stiffer braid is required to prevent buckling.

FIVE-FOOT MODEL

Many of the preliminary tests were carried out on structures built from 1/8′′ diameter five-foot long FRP rods (Figure 2). With 12 rods per axis (24 total), each strand intersects seventeen other



5 Biaxial tower at the TAIT testing facility, showing transformation from an open top to a closed top, tapered structure.

perpendicular strands, including those at the top and bottom boundary of the cylinder. This provided an inexpensive platform on which rigging systems could be quickly mocked-up, and the geometry could be pushed to its theoretical limits.

It was with this system that analytical models were compared and verified. In this instance, both the top and bottom diameters were maintained, the top at nearly $1/5^{th}$ the diameter of the bottom. This configuration produced a stable bottom-heavy tower throughout transformation and served as a useful model to simulate behavior of larger subsequent versions.

TWENTY-FOOT MODEL

A tower prototype with twenty-foot-long rods was constructed as the next step towards scaling the braided fiberglass rod system as development moved toward larger-scale structures (Figure 4). The 20′ tower was also a working model to physically test the transformation behaviors while working to match digital analytical simulations developed in parallel. This allowed both the design and engineering teams to align different characteristics of the digital and physical simulation of the tower under different loads and transformations. The 20′ tower was constructed from forty-four 3/8′′ pultruded fiberglass rods. The rods were braided biaxially flat on the ground and then closed into the final cylindrical tower while standing. Rods that were of opposing braid directions were then connected at nodes constructed from tube sleeves that were pinned together at the ends with socket-head cap screws and lock nuts to allow them to remain tight, but still allow for a pinned movement during the transformations of the structure.

Initial tests were conducted without a top or bottom ring to constrain the diameter of the structure. Without constraining the edges of the braid, the dead-load weight of the rods caused the structure to compress in a sagged position over time. We worked together with the engineering team to test different scenarios of constraint to adjust this tendency. We then conducted various loading studies to determine the deformation and behavior of the tower under different loads. Once constrained, the structure was able to maintain its shape under load as long as the rods did not buckle.

Although the scaling of the structure from a five-foot to a twenty-foot working prototype revealed that the structure and characteristics of the structure do not scale linearly, we were able to account for the differences in the two prototype systems using scaling laws. This allowed for a better understanding of the relationship between rod diameter and length to the overall weight and performance of the structure.

FIFTY-FOOT TOWER

This work lead to the construction of a fifty-foot-tall version of the biaxial tower in collaboration with TAIT Towers at their Pennsylvania testing facility. Synthesizing previous tests and simulations, the tower was initially tested with its uppermost edge unconstrained. Doing so clearly demonstrated the potential

6 Final installation of the biaxial braided tower.

for dramatic large-scale transformation (Figure 5). Nylon cables were again used to manually pull the braid into a variety of forms. This structure was eventually installed on-site with a ring constraining the top edge of the braid (Figure 6).

CEILING-MOUNTED STRUCTURES

By hanging the structure, the ground below can be made more accessible. In this scenario, the braided elements also work in tension rather than compression, so the stiffness of the rods is not a design factor. In this orientation, the structure can be easily implemented as a transformable room or space divider. When not in use, it can be pulled up and out of the way, leaving the ground clear for another use. However, this inverted mounting brings its own design constraints. When hung from the ceiling the structure does not support its own weight and naturally tends toward elongation. The flexibility of the strands adds to the force necessary for upward transformation. To counter this, a rigging system may be fitted with counterweights or some other mechanical advantage.

TRANSFORMABLE MEETING SPACES

The Transformable Meeting Space attempted to re-imagine interior office and living environments through transformation (Figure 1). There are two predominant approaches to office design: open spaces and fixed offices. Both design strategies have significant challenges. Open office plans have been shown to decrease productivity due to noise and privacy challenges, yet they provide flexibility and collaborative opportunities (Kim and de Dear 2013). Fixed offices offer privacy and quiet environments, but restrict the type of working spaces available and occupy more square footage. This research proposes an alternative, whereby structures can easily transform between private rooms, lounge spaces, or other quiet meeting spaces into open flexible areas. This project leveraged the kinetic potential of biaxial braided structures to create a meeting room for six to eight people or morph into the ceiling, leaving a clear and open area below. The lightweight but structural properties of the biaxial braid allowed the rigid space to neatly transform with little effort.

Constructed from five 3/8″ diameter, ten-foot-long FRP rods, the edges were constrained, with the bottom diameter slightly smaller than the top. A system of nylon cables hoist the bottom edge from eight points simultaneously. These ropes all terminate

7 Four of the 64 possible configurations of the Transformable Screen.

at a pair of counterweights, one inside and one outside of the structure. By pulling on these weights from either the outside or inside, the user is able to easily overcome the friction that holds the structure in place. Once inside, the user can lower the structure by pulling down on an internal cable (Figure 8).

The Transformable Meeting Space is clad in a bilayer skin of natural felt and wood veneer. These two materials are laminated to create flexible strips with acoustic dampening. Affixed to every rod along one axis of the braid, these strips overlapped slightly to create a completely opaque shingled surface. The felt interior surface provides acoustic separation from the outside. Constraining the bottom edge at a smaller diameter provides a slight overhang from which the felt-wood sheets hang. In the transformation of the structure, these strips easily slide by one another without introducing excessive friction, ultimately nesting into a tight coil.

TRANSFORMABLE SCREEN

The ability to attach felt and wood cladding attests to the strength and adaptability of this biaxial structure. However the cladding can also been seen as an unnecessary addition to the system. The strips were not integral to the structural system itself, rather they only provided the enclosure and acoustic properties. The ultimate goal is to symbiotically blend structure and surface. The Transformable Screen was designed to solve this and to further integrate surface into the kinetic structural system.

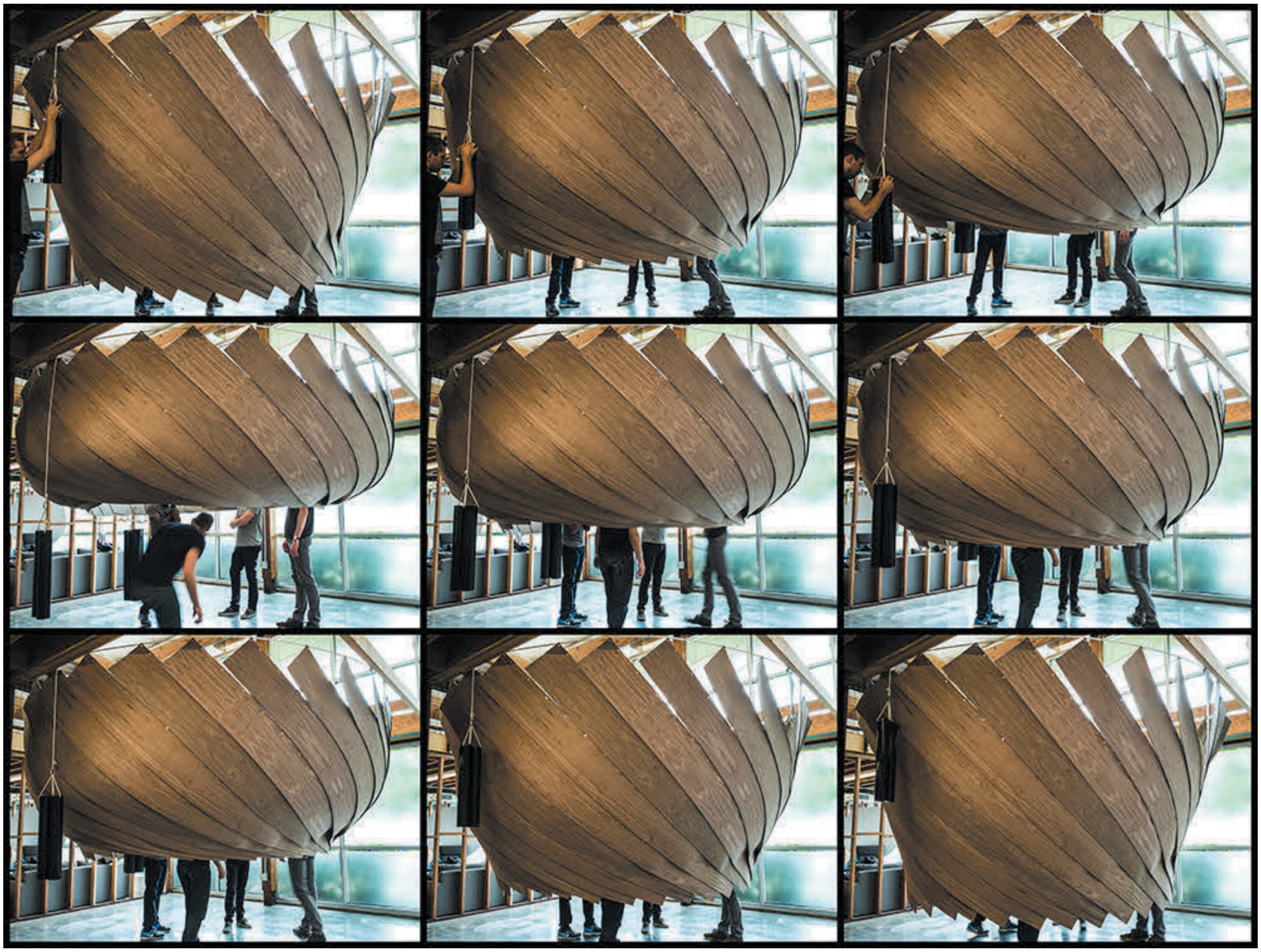
Tanking cues from the works of Sean Ahlquist and Zaha-Hadid Architects, which explore computationally derived minimal-textile surfaces, we exploit the loose tolerance of stretched textiles to produce a transformational system. Like the biaxial braided system, energy stored within fiberglass splines or stretched textile allows for structurally consistent transformations.

The Transformable Screen was designed as a room divider that can be deployed and transformed to create a variety of different working spaces. When fully deployed, three separate working spaces are created; when fully retracted, the entire room is exposed. In between these extremes, users are able to deploy or retract portions of the screen to create 64 different working spaces (Figure 7).

A single 54′ long piece of elastic 3D-knit fabric is held in tension by five steel ribs running through evenly distributed pockets along its length. These define four sections, each 18′′ in height. Hung horizontally from the ceiling, the uppermost rib is made from a rigid 1 1/4′′ by 3/16′′ flat stainless steel bar. Subsequently lower rods are made from 5/16′′ stainless rod.

Cut at 88% of the length of the ribs, the fabric is stretched into this final dimension of 54 feet. By doing so, the fabric bows, creating a minimal surface wherever the ribs curve. Stretched to 113.6% of its original length, the fabric accommodates the vertical transformation of the rails at various points along its length while remaining taut. The screen is fitted with six independent points from which the structure may be vertically raised. As such the structure is able to assume 64 different configurations of up and down positions, not including mid-height or variable configurations. The lower ribs are fitted with pivot nodes at seven points along their length, allowing various zones to transform without affecting neighboring zones. Since this system is not closed into a cylinder, it could have nearly infinite length.

This approach developed out the of biaxial braid in an attempt to simplify and separate the axes of the braid, having rods run



8 Demonstrating the use of Transformable Meeting Spaces.

in a single direction. In this case they run along the structure. Like the braid, the internal tension of two opposing forces, the compressed rods and the tensioned fabric, provide rigidity and continuity during transformation. The tensioned fabric neatly scallops proportionally as the structure retracts, and smoothly blends between retracted and deployed portions of the screen. This particular approach likely only works when hung from above. As such, Transformable Screen is best suited for indoor space division or hanging configurations rather than free-standing structures.

CONTRIBUTIONS

We envision a future for architecture, design, and construction that is transformable, lightweight, and sidesteps the current electromechanical paradigm. Toward this end, we have developed structural systems with braided structures and minimal materials. While kinetic architecture has historically relied on complicated armatures, hinges, and actuators, we aim to produce structures whose every part contributes to the effort of transformation, integrating surface and structure.

We have shown how biaxial braided structures can be used to create lightweight large-scale spatial transformation. By starting with braided structures, we allow the internal network of strands to dictate the transformational range and stability. These transforming structures are designed from a simple set of conditions: strand length, thickness, stiffness, and braid tightness. The transformational possibilities of any given structure emerge from these conditions and can only be revealed through testing and correlated simulation. We have demonstrated the use of custom software for the simulation of biaxial braided structures, allowing the designer to anticipate the possible range of the structure prior to final fabrication.

This research uncovers the hurdles that must be resolved when scaling these structures. For example, with the biaxial braided tower, wind speeds eventually pushed the tower beyond its limits, causing it to buckle. The likely conditions that caused this were reproduced with the simulation software afterwards. Ultimately, it was concluded that constraining the structure's diameter in the middle, in both compression and tension, would have adequately resisted the wind and created more stability, but would have constrained the possible range of motion.

For this reason we then explored hanging systems as opposed to freestanding structures. In the most recent iteration, aiming to reduce weight and complexity, we moved to a textile system with a single axis of rods, creating the largest and most versatile system built to date. Tension applied to the textile induced a minimal surface, which allowed the entire surface to maintain rigidity despite localized transformations of the structure.

Looking forward, we see these structural approaches adopting the automation techniques of the textile industry. By piggy-backing onto established industries we see the feasibility and stability of these systems. Large-scale transforming structures could be rapidly produced without the need to specify an application.

We see this research as the first steps towards producing lightweight, large-scale transforming structures. From stadium roofs, retractable canopies, concert venues, or other types of performances, transforming architectural structures are increasingly valuable, yet traditionally require excessive cost, assembly complexity ,and power. Our aim is to create a future of morphable architectures that simplifies this structural performance to minimal surfaces with textile-like transformations.

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IMAGE CREDITS

Figure 1: Skylar Tibbits, 2016

Figure 2: Jared Laucks, Aran Chadwick, 2016

Figure 3-6, 8: Skylar Tibbits, 2016

Figure 7: Skylar Tibbits, 2017

Self-Assembly Lab is a cross-disciplinary research lab at MIT, developing self-assembly and programmable material technologies aimed at construction, manufacturing, product assembly and performance. The lab is composed of engineers, scientists and designers who are transforming commonplace materials into programmable materials that can assemble themselves, and sense and react to their physical environment. The Self-Assembly Lab is working with academic, commercial and government partners to develop new technologies and fabrication processes that are finding their way into everything from art installations to clothing, cars, planes and building components.

Atelier One is a structural engineering firm based in London, Manchester, and Brighton. For nearly twenty years, Atelier One has worked with many talented architects, artists and designers, both within the UK and internationally. Completed projects include the award winning Conservatories & Super trees at Gardens by the Bay in Singapore, (World Building of the year 2012), the development of Federation Square in Melbourne (Australian Architects Prize 2003, Australian Engineering Excellence Award 2003), the National Stadium in Slovenia and, in the UK, the Baltic Gallery in Gateshead and three specialist buildings for the prestigious White Cube Gallery in London.