THE UNDERWOOD PAVILION

An investigation in parametric tensegrity structures

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Abstract. Tensegrity structures are not commonly found within the current discourse of architecture. The reason may be that they can only be designed through physical form finding processes. This paper will show how architects can gain the ability to design these structures digitally utilizing physics engines that simulate these form finding processes in real time. To demonstrate this, the paper will use the Underwood Pavilion as a case study to describe a design process that replaces traditional methodologies by digital methods, suggesting a new parametric design approach for lightweight structures and envelopes.

Keywords. Tensegrity; parametric; membrane; pavilion; modular.

1. Introduction

The Underwood pavilion was the result of a Digital Design Build Studio taught by the authors at Ball State University during the summer of 2014. The goal of the studio was to develop a portable pavilion for the University’s hometown of Muncie, Indiana. The project was funded through a series of Departmental grants as well as supported by the Muncie Makes Lab, a local community organization. This paper will first outline the course structure and introduce the problematic associated with the designing of complex tensegrity structures. The paper will then explore a unique process, through the utilization and creation of new tools within Rhinoceros 3d, Grasshopper, Galapagos and Kangaroo through which students were able to design and
fabricate a parametric system allowing for the design and aggregation of tensegrity modules which formed the pavilions structural envelope.

2. Course structure

The course was run as an intense, five-week Digital Design Build Studio consisting of eight graduate students.

To meet the projects extremely tight schedule the course organization was rigid, yet allowed for a high level of flexibility in design opportunities as no initial formal constraints were given. Throughout the first week, the students self-organized into a series of four collaborative research based think tanks. Based on group interest, each research group created a general overview to identify unique aspects of computational design in relation to envelope, structure and material. Following the first week’s completion, the think tanks presented their outcomes as proposals and decided to further investigate the creation of a tensegrity structure clad in tensile fabric. Rather then utilizing the traditional model based means of form finding, students decided to rethink the process through the creation of novel structural simulation tools within Rhino 3d and Grasshopper.

![Figure 1. Underwood Pavilion at night](image)

During the second week four new teams were formed: Team A investigated methods for the computational programming of tensegrity systems. Team B
investigated materials, performed cost analysis as well as tested full-scale structural mock-ups for feasibility. Team C specialized in fabrics (typologies, material properties and modelling). Team D investigated techniques for the creation of both digital and physical representations of tensegrity structures.

Throughout the third week, a series of design charrettes, in-class workshops and critiques with outside experts and structural engineer consultations helped finalize the project’s formal and material pallet.

During week four, students acquired materials and prepared for fabrication. Small and large-scale prototypes were fabricated from standard materials allowing for rapid prototyping. Environmentally friendliness, long-term durability and efficiency were major criteria during the final selection of materials. After many intense studies, aluminium pipes were chosen for the compression struts, galvanized steel cables for the tension members and Elastane, an elastic membrane for the envelope.

The fifth week was used for in-house fabrication, structural testing and initial assembly. Three individual teams first prepared all of the module’s components: Team One fabricated all Aluminium Compression Members. Team Two oversaw the preparation of all tension members and Team Three fabricated all tensile fabric components. Students setup fabrication and assembly spaces throughout the Department that allowed for them to collectively and rapidly assemble and structurally test all the modules and elements in teams of three.

On site assembly was accomplished in only two days. Bundling of the module’s cables and struts before transporting allowed for quick and easy re-assembly of the modules on the site. Finally, the modules were assembled, joined and skinned.

3. Tensegrity structure

The Underwood Pavilion was built from forty individual tensegrity modules linked together creating the final overall form.

Different from conventional construction systems that are based on continuous compression under gravitational loads, tensegrity systems are based on the concept of continuous tension. Rather, these systems are similar to the structures within the human body where bones act as compression struts and the muscles, tendons and ligaments form the tension members (Ingber, 1998). What R. Buckminster Fuller (Fuller, 1973) defined as tensegrity structures is still unique: Isolated compression members and a continuous path of tension members that connect all nodes.

The advantage of utilizing a tensegrity structure for the pavilion was that the system could be lighter, stronger and more cost efficient than conven-
tional structures such as space frames or truss systems. Another advantage was that materials could be optimized more effectively since the struts work in pure compression while the cables work in pure tension.

Nonetheless tensegrity structures cannot be predicted from their geometric characteristics alone. The design process must take into account that a tensegrity moment can only be achieved through a structural equilibrium. Several methods of mathematically calculating tensegrity structures exist and are outlined in papers such as Tibert and Pellegrino (2003). Nonetheless, these methods are difficult to apply within a rapid design process, especially in the case of more complex tensegrity structures that must also respond to spatial and environmental challenges. New tools such as the Rhino 3d’s plug-in Rhino Membrane, the Grasshopper plug-in’s Kangaroo and Galapagos offer for the first time graphic design systems for a high level of complexity that take the physical material properties into account. Both applications enable form finding and the structural solving of tensegrity systems through a methodology of finite element analysis. This provides real-time feedback of structural behaviour in both individual and aggregated modules, a necessity within the geometric form-finding processes of the pavilion.

4. Parametric module form finding

A 3-strut tensegrity module was chosen as a base constraint that helped minimize the solution space in designing the individual modules and the pavilion. The chosen base module consisted of two equilateral triangles with end faces of differing sizes that were parallel to one another. The upper face was named “ABC,” the lower face “DEF”. Tensile cables connected the node pairs “AD,” “BE,” and “CF,” while rods connected the node pairs “AE,” “BF,” and “CD”. Within these constraints four types of variation were defined: 1) The distance between the upper face and the lower face (unknown variable), 2) The scale between the upper face and the lower face (defined variable). 3) The length of the tensile members between the two faces (defined variable) and 4) The module’s rotation, which was a consequence of the previous variables and the tension necessary to stabilize the geometry in a tensegrity state (unknown variable).

To find the optimal formal geometry as a resultant of combining these sets of variables, two physical experiments and one digital simulation were conducted. Rubber bands were used for the first physical models to approximate length of cables for struts of different lengths. Based on the outcome of the first set of models, a second set of physical models were developed in which the rubber bands were replaced with strings. Within these studies, minor adjustments were necessary to find the final resting length of strings and
their corresponding struts allowing for the models to reach a stable tensegrity state. These physical models created a simplistic starting point for the digital simulation.

4.1. PARAMETRIC FORM SOLVING

Rhino Membrane, Grasshopper, Galapagos and Kangaroo were utilized for the project’s simulation. Rhino membrane, a plug-in designed for Rhino 4.0 was used for initial module form finding, digital feedback and enclosure optimization.

Galapagos was used on singular modules to find an optimal geometric fitness for the two unknown values of rotation and distance between faces (Figure 2). Galapagos was also used for real-time feedback when manipulating individual module proportions, while continuing to maintain a high level of mathematical accuracy (solutions within a thousandth of an inch). Through Galapagos, variation of individual modules could be created (through a series of number sliders or value inputs), compared and directly implemented into the Kangaroo solver for interpreting the overall form. Through this workflow, designers were able to continually modify the pavilion’s overall form through the manipulation of a single module’s variable.

Kangaroo, a Live Physics engine for interactive simulation, optimization and form finding developed as plug-in for Grasshopper was used to simulate each possible outcome achieved through the aggregation of modules. By defining a series of attractor points in the location where compressive rods and tensile cable intersect, the software enabled linking the individual modules into a single continuous system. With the connection of the cables and struts, the overall form slowly recalculated and found its form in equilibrium.

When reconfigured and combined, these applications enabled the designers to define the final form through the definition of all necessary points of connection, as well as forces on all struts and cables. The resultant of the simulation was then revised through the manipulation or removal of individual modules to allow for asymmetrical deformation to the initial form, while minimising excessive tensile forces that would be encountered during construction.

4.2. MODULE PROGRAMMING

Each module variation was first constructed in Rhino then parameterized. Rather than the elastic properties of the rubber bands in the physical model, the cables in the digital model were defined by a determined pre-stress value and length. The modules were then connected into rows of single modules. Utilizing customized digital physics simulations allowed the designers to
precisely predict the curvature of linear aggregations of specific module variations.

Following this, single rows were doubled. This time the physics simulation visualized a shift within the arch, which was perpendicular to its curvature. The shift occurred as a consequence of the individual module’s rotation. In the final simulation, the modules were arranged into aggregates of ten by ten modules. The structural and formal behaviour of aggregates constructed from different module variations and combinations were then compared through digital simulation.

5. Module Aggregation

Developing the pavilion from a set of module variations allowed exploring different strategies to aggregate the module in different fields. In each, one top face must connect to other top face and bottom face to other bottom face. The smaller top triangles define the inner surface of the pavilion while the larger bottom triangles define the outer surface. In order to form a Tensegrity structure from a pattern of individual Tensegrity modules, the edges of individual triangles must always connect to the midpoint of edge of neighbour-
ing triangles. Further, it was experienced that additional porosity and structural flexibility could be created by skipping every second module in every second row while still providing the continuity necessary for a singular tensegrity system. This allowed the designers to create larger and smaller apertures within the pavilion’s envelope. Changing the scale between the top face and the bottom face of each module enabled further manipulation of the pavilions envelope.

6. The integration of physical modelling and prototyping

The complexity inherent to computationally calculating tensegrity structures, led students to create a continuous feedback loop; first testing ideas in physical models, than confirming their outcomes digitally. On the other hand digitally confirmed results were immediately tested as physical prototypes. This feedback loop between physical and digital modelling allowed for complex problems to be detected and solved quickly.

Precise and highly descriptive models became a necessity, as time throughout the semester was extremely limited. Designers learned to track the complex behaviours of individual elements and modules within the structure by creating very simple numbering, colour, and vector based systems. Tying a simple coloured string to repeating elements in a physical model or a coloured vector in the parametric model for example, allowed students to easily find corresponding connection points. Understanding methods of physically and digitally tracking behaviours of individual components within
a larger system played an important role during full-scale construction, where connections become extremely complex.

Working both with individual modules and complex aggregations, students learned to quickly understand the effects small changes on a component could have on the pavilion as a whole. Varying size or tension in a single module could affect the shape, structure and rotation of the entire form.

Full-scale prototyping was an important feedback mechanism within the studio. If an individual or group had a proposed design idea, it was immediately necessary to test its workability, availability as well as cost effectiveness. If any of these could not be found or achieved, the designers immediately revised their idea or merged with the design process of another group.

Initial testing also aided students in the rapid prototyping of joints, connectors and details. As prototyping happened during the design process, students were able to test many variations within the mock-up of a single module. For example, one module contained a total of one sheet of fabric, six joints, nine cables and twenty-seven connectors. Therefor in the testing of one module, designers could test a variety of connections and parts for aesthetics, compatibility and structural integrity. Because of this integrated process, many potential on-site construction issues were confronted early on in the design process.

With only one week for fabrication and construction, it was imperative that a robust production system was designed and implemented. While prototyping, students developed a step-by-step fabrication process utilizing individual strengths, machines and space to maximize efficiency.

7. Module Construction

The final Tensegrity state of a module can only be reached with all members in tension or compression. The entire system remained loose until the final turnbuckle is attached. The modules can be stacked and transported efficiently as a loose low-volume bundle of bars and cables (3” x 3” x 6’). At the site of construction, only a single cable per module had to be joined to create the final module’s form. Each module described a volume that varied between 3’ x 3’ x 3’ and 4’ x 4’ x 4’. This enabled the designers to move all modules to the site in their most compressed form while maintaining a level of formal adjusting through the manipulation of member tensions on site.

Since cables were in pure tension and struts in pure compression, the axial deformation of struts and cables was negligible. This enabled the use of lightweight materials: 1” diameter aluminium tubes and 1/8” galvanized steel cables were used for the pavilion’s final structure.
Cables were pre-cut to length for each of the 9 nodes per module. Precise grooves and holes within the aluminium tubes facilitated the locking of the cables in place through the use of simple cable stoppers and pins.

By inserting a turnbuckle at the centre of the final connecting cable, stress was easily regulated within the modules until each unit had snapped into its predicted final geometry; individual modules tension could be adjusted to reach the final form.

Once all of the modules were connected the entire structure was anchored. Standard 30” earth anchors were used to secure the pavilion from wind and snow loads.

8. Envelope

With all of the modules assembled on the site each individual module was fitted in an elastic fabric. The ends of the three struts were used to span the fabric. As a result the fabric enclosed the struts within a minimal volume defined by the elastic qualities of the fabric.

Elastane, a stretchable fabric originally used for sportswear was adapted to create the pavilion’s skin. Created by filaments that are more durable than non-synthetic materials such as rubber, Elastane can also be derived from 84% recycled polyester.

Finding the precise pattern for cutting the fabric required taking a stretch factor of 40% into account. This was derived from experiments utilizing a 1/1 scale module prototype. Having studied the elastic behaviour of the material, students digitally modelled the fabric in Rhino Membrane. The 3d model was then unrolled with the holes necessary to connect the fabric to the struts. The final fabric pattern was calculated to a width of 62”, the same width of the fabric roll offered by the supplier. This minimized material waste.

The modules were “dressed” after the entire structure of the pavilion was assembled. This affected how the fabric was unrolled and the pattern was developed. After the dressing of the pavilion, each module divided an enclosed volume that as a pattern created a self-shading system. The self-shading structural envelope created a cool environment in the hot summer months of Indiana, and as a windbreak in the cooler fall months.

9. Conclusion

Tensegrity structures have large advantages over other structural systems. They are through their use of predominantly tension members lighter and stronger then conventional systems. The systems materials can be optimized
in a more efficient ways since their components work either in pure tension or compression.

The use of a parametric tensegrity structure had in the case of the Underwood Pavilion proven effective as a temporary structure because of its self-erecting behaviour and its range of adapting geometry. Simplistic and precise details within the pavilion proved that using complex tensegrity structures for a small-scale enclosed structure can still allow for a fast and accurate assembly process while maintaining the possibility of collapsing a mobile pavilion into bundles of cables and rods for easy transportation. The findings from structural simulation and from the construction of the pavilion itself will allow for further prototypes to explore the possibility of more irregular tensegrity systems which respond to new sets of parameters in the future.

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