Underwood Pavilion

A Parametric Tensegrity Structure

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Abstract

Recent advances in real-time structural analysis has given architects the freedom to design and manufacture forms and structures that previously would have been difficult if not impossible to achieve. Until recently these advances had not been seen as a driving force within the area of asymmetrically designed tensegrity structures. This paper presents a new design method that is integrating analysis tools into a computational design process. Through the lens of the recently completed *Underwood Pavilion* this paper demonstrates how this process of designing tensegrity structures can be streamlined. This process allows for greater access to such structures and a higher level of flexibility in designing tensegrity systems by the design community at large. Acting as a case study, the *Underwood Pavilion* describes a process where traditional methods of form finding are complimented by a new parametric approach to design tensegrity based lightweight structures and envelope systems.

Keywords:
tensegrity, parametric, membrane, pavilion, modular

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Figure 1. Exterior view of Underwood Pavilion.

1. Introduction

The *Underwood Pavilion* was Prof. Riether's and Prof. Wit's first successful attempt at fabricating a full-scale tensegrity prototype through a novel parametric framework. The pavilion defines a space that can comfortably be inhabited by a group of 12 people. Located close to Muncie, Indiana, it creates a permanent destination for hikers and cyclists. Accomplished through a 5-week summer workshop held at Ball State University in Muncie, Indiana, a team of 8 students and faculty collaborated in the development of the design, fabrication, and construction of the project. This paper discusses in detail the developed tensegrity design methodology and the accomplishments and difficulties encountered throughout the project's overall development. It also discusses the project's workflow and a unique design, fabrication, and assembly process created through the development utilising Rhinoceros 3d, Grasshopper, Galapagos, and Kangaroo. Through the development of an integrated digital/manual workflow, the team was able to develop a parametric design method that allowed for the design of variable tensegrity modules that, once aggregated, generated the form of the *Underwood Pavilion's* unique visual and structural envelope.

2. Background

Unlike conventional construction systems centred around the concept of continuous compression under gravitational loading, tensegrity structures utilise a concept of continuous tension. In contrast, tensegrity systems are similar to the assemblies 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 (1973) previously defined as tensegrity structures is still unique: isolated compression members and a continuous path of tension members that connect all nodes.

Examples of how tensegrity structures are applied to an architectural scale are projects such as the Warnow Tower (Volkwin, 2003) in Rostock, Germany, the tallest tensegrity mast ever deployed, and the Kurilpa Bridge (Cox Rayner Architects, Arup, 2009) in South Brisbane, the world's largest hybrid tensegrity bridge. More recent research by Kenneth Snelson also exemplifies the system's unique properties and brings tensegrity into the forefront of design thinking.

Tensegrity structures are relevant to architecture since they are lighter, stronger, and more cost efficient than other structural systems such as space frames or truss systems. Additionally, the system where all struts work in pure compression while cables remain in pure tension allows for a more effective use of material and nominal dimension optimisation.

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Nonetheless, the geometry of tensegrity structures is more difficult to design than other structural systems. Tensegrity structures cannot be predicted from their geometric characteristics alone. The design process must take into account that a tensegrity moment can be achieved only through a structural equilibrium within the system. Several methods of mathematically calculating tensegrity structures exist and are outlined in papers such as Tibert and Pellegrino (2003). Nonetheless, these complexities within these methods are nearly impossible to apply within a rapidly adapting design process, especially in relation to a more complex overall form, asymmetrical loading or environmental conditions.

Recent tools such as the Rhino 3D plug-in Rhino Membrane and the Grasshopper plug-in Kangaroo in conjunction with Galapagos offer for the first time graphic design interfaces for a high level of geometric complexity which also have the ability to take 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 behavior in both individual and aggregated modules, a necessity within the geometric form-finding process of the *Underwood Pavilion*.

3. Parametric Tensegrity Structure

Typically, tensegrity structures are realised as a singular continuous system, where all parts are reliant on all others within the system. Although this has advantages such as material and part optimisation, the complexity inherent within solving and fabricating the overall system as a singular object was not desirable. Rather, the *Underwood Pavilion* visualised the tensegrity system as a series of self-contained modules with the ability to be individually programmed, fabricated, tensioned, and inserted/removed from the structure without causing catastrophic failure of the overall system. Through the unique programming of individual modules and the removal of modules from the overall system, the resulting pavilion was able to create formal deviations that would have been difficult to realise through a traditional continuous tensegrity system.

To facilitate the modular system, a variant of a 3-strut tensegrity module was chosen as a base constraint that helped minimise the solution space in designing the individual modules and the pavilion as a whole. The chosen base module consisted of two equilateral triangles with end faces of differing sizes 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 the typology of the module could vary based on two variables that could change (defined variables) and two variables that would change as a consequence (unknown variables):

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Defined variable 1:
Scalar variation between the upper face (ABC) and the lower face (DEF).
Defined variable 2:
Length of the tensile members between the two faces (ABC) and (DEF).
Unknown variable 1:
Distance between the upper face (ABC) and the lower face (DEF).
Unknown variable 2:
Module rotation between upper face (ABC) and lower face (DEF), which was a consequence of the previous variables and the tension necessary to stabilise the geometry in a tensegrity state.

To initially test the system, two physical experiments were conducted. Rubber bands were used 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, adjustments were necessary to find the final resting length of strings and their corresponding struts allowing for the models to reach a stabile tensegrity state. An aggregate of modules was built, then the variables of the module were changed, and another system was constructed. A series of aggregates showed the impact of the different module's geometry on different overall forms. Some of the aggregates twisted or curved more than others. Some aggregates started to define more enclosures than others.

These physical models created a simplistic starting point for the design method that was then developed computationally. In replacing the physical studies with a parametric model the goals were (1) to test different variations by changing one model, rather than building a separate model for each variation that the team wanted to test; (2) to achieve a more precise understanding of how varying the module may affect the overall form; (3) to test aggregations too complex to build in a physical model.

3.1 Parametric Form Finding

Tensegrity systems have been applied to projects at large scale before. But the examples mentioned earlier showed that only very basic overall forms had been used: In the case of the Warnow Tower or the Kurilpa Bridge, modules were assembled into a straight line. In the case of Buckminster Fuller's studies, the overall form was a sphere. The design process developed for the *Underwood Pavilion* was different. Rather than starting with an overall form, the form emerged from the aggregation of variations of modules.

To develop the design process of such a system, Rhino Membrane, Grasshopper, Galapagos, and Kangaroo were utilised. Rhino membrane, a plug-in designed for

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Figure 2. Interior view of Underwood Pavilion.

Rhino 4.0, was used in conjunction with physical modelling as a means of initial module form finding, digital feedback, and enclosure optimisation.

Galapagos, an evolutionary solver, was utilised on singular modules to find optimal geometric fitness for the two unknown values of face rotation and distance between the upper and lower faces. The plug-in was also used as a means of obtaining real-time feedback when manipulating individual module proportions, while still maintaining 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, the designers were able to continually modify the pavilion's overall form through the manipulation of a single module's variables. To verify the parametric modules outputs and internal tensions during the aggregation process, each selected variation was fabricated and tested at small scale.

Kangaroo, a live physics engine for interactive simulation, optimisation, and form finding developed as a 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, individual modules were linked, creating a single continuous system. With the connection of the cables and struts, each of the formal iterations slowly recalculated and found their form in a state of equilibrium.

Although initially the overall form is an unknown, the reconfigured and combined tools enabled the designers to define the final form through the definition of all module types in relation to their necessary points of connection as well as the desired strut and cable network forces. The overall form was also impacted by removing modules to create openings for views or an entrance, creating asymmetric deformations in the overall form, while simultaneously changing tensile forces within the aggregate.

3.2 Module Programming

Each individual module variation was first constructed in Rhino then parameterised: 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 fixed length. The modules were then connected into single rows of modules. Utilising customised computational physics simulations allowed the designers to precisely predict the curvature of linear aggregations based on specific module variations.

Following this step, single rows were doubled. This time the physics simulation visualised 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 6 x 6 modules.

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The structural and formal behavior of aggregates constructed from different module variations and combinations were then compared through digital simulation.

3.3 Module Variation

As the overall form functions as a continuous network, simply replacing one module with another was not possible. Rather, the integration of a new module type would in turn, redefine the form and parameters of all adjacent modules. Varying a module in the physical model required the construction of an entirely new aggregate. In the digital model the team was able to instantly recalculate the formal properties of the entire aggregate and output their parameters for fabrication. In a further development one could also think about using multiple module variations within a single system.

4. Aggregation

Developing the pavilion from a set of varied modules allowed for easy exploration of novel strategies for aggregation through different field conditions. When connecting modules, one top face (ABC) must connect to other top face (ABC) and bottom face (DEF) to other bottom face (DEF). The smaller top triangles defined 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 midpoints of edges of neighbouring triangles.

Although during computational modelling and simulation force values were calculated to be minimal, it was found otherwise during construction. Although each module was fabricated from the exact simulated measurements, it was found that slight inconsistencies during assembly, individual module tensioning, material flexure or stretching, and finally inconsistent siting conditions created conditions where tensions could be nearly unmanageable or self-destructing. To bypass these inconsistencies, a system was developed for internal stress management.

Rather than reworking the entire tensegrity system to minimise unpredictable force accumulation, a system was developed where individual modules could be eliminated from the system creating view apertures while also reducing stress. This porosity and structural flexibility was created through the skipping of every second module in every second row. Although removing elements in a single continuous system would cause failure, even with the removal of modules within the modular based system, enough continuity still existed for the creation of a successful tensegrity system. This variable allowed the designers to create large or small apertures within the pavilion's envelope. Changing the scale between

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the top face and the bottom face of each module also enabled further manipulation of the pavilions envelope.

5. The Role of Physical Modelling and Prototyping

Digitally confirmed results were immediately tested as physical prototypes insuring the correct translation of data. This feedback loop between physical and digital modelling allowed for previously complex complications to now be detected and solved quickly.

As modules appear very similar and can become disorienting during construction, designers learned to track the complex behaviors 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 the team to easily find corresponding points of connection. Understanding methods of physically and digitally tracking behaviors 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, the team learned to quickly visualise the effects small changes on an individual 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 also an important feedback mechanism. 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, it was necessary for the designers immediately revise their idea to make it feasible.

Initial testing also aided the team in the rapid prototyping of joints, connectors, and details. As prototyping happened simultaneously with the design process, the team was able to test large numbers of variations within the mock-up of a single module. For example, a single module contained a total of one piece of fabric, six joints, nine cables and 27 connectors. Therefore, 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 a single week for fabrication and construction, it was imperative that a robust production system be designed and implemented. While prototyping, the team developed a step-by-step fabrication process utilising individual strengths, machines and space to maximise efficiency.

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6. Module Construction

The final tensegrity state of a module can be reached only when all members are in tension or compression. The entire system remained loose and in a flat pack orientation until one final turnbuckle per module was connected and tightened. In the untensioned state, the modules can be easily stacked and transported as a loose low-volume bundle of bars and cables (roughly 3″ x 3′ x 6′). At the site of construction, only a single cable per module was joined creating the final module's form. Each of the 40 individual modules described a volume that varied between 3′ x 3′ x 3′ and 4′ x 4′ x 4′, respectively, and weighed less than 5 pounds. This ease of assembly and scale of module allowed for the module to be maneuvered around the site in a compressed form, then simply tensioned and moved into its corresponding location by a single individual.

Since cables were in pure tension and struts in pure compression, the axial deformation of struts and cables was visually negligible under full loading conditions. This enabled the use of lightweight materials such as 1″ diameter aluminium tubes and 1/8″ braided galvanised steel cables were used for the pavilion's final structure.

The cables were pre-cut to length for each of the 9 nodes per module. Precise grooves and holes within the aluminium tubes were created though the implementation of a flexible jig and facilitated the fixing of the cable positions, through the use of simple crimped cable stoppers and pins.

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

During the process of connecting modules, after every few connections it was necessary to lift the pavilion in progress off the ground to allow the structure to find its equilibrium. This process also aided in keeping internal stresses down was achievable all the way to the end with only three to four individuals.

The *Underwood Pavilion* was fabricated from 40 interconnected tensegrity modules. After all of the modules had been connected, the overall structure was anchored. Standard 30″ earth anchors were used to secure the pavilion from wind and snow loads.

7. From Tensile Enclosure to "Tensegrity Fabric"

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

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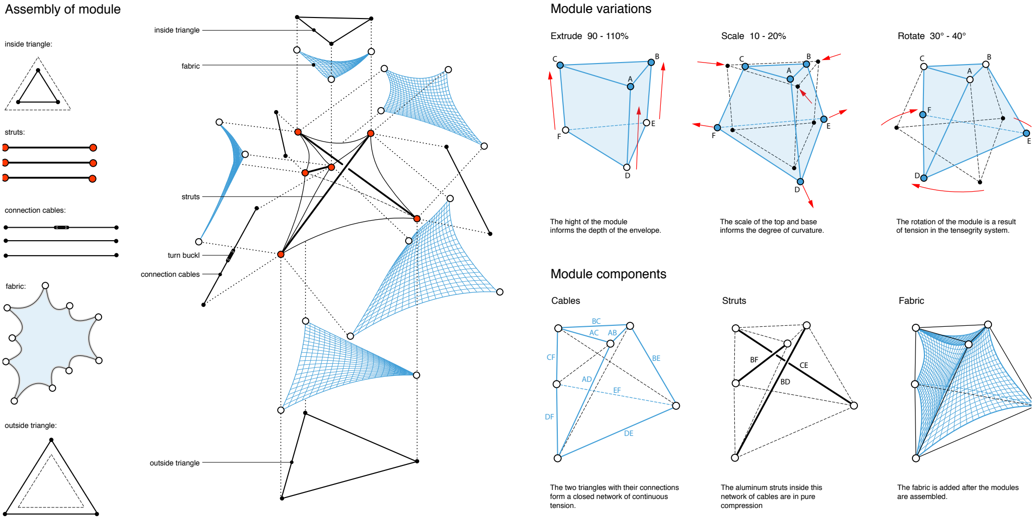

Figure 3. Assembly and variations of module.

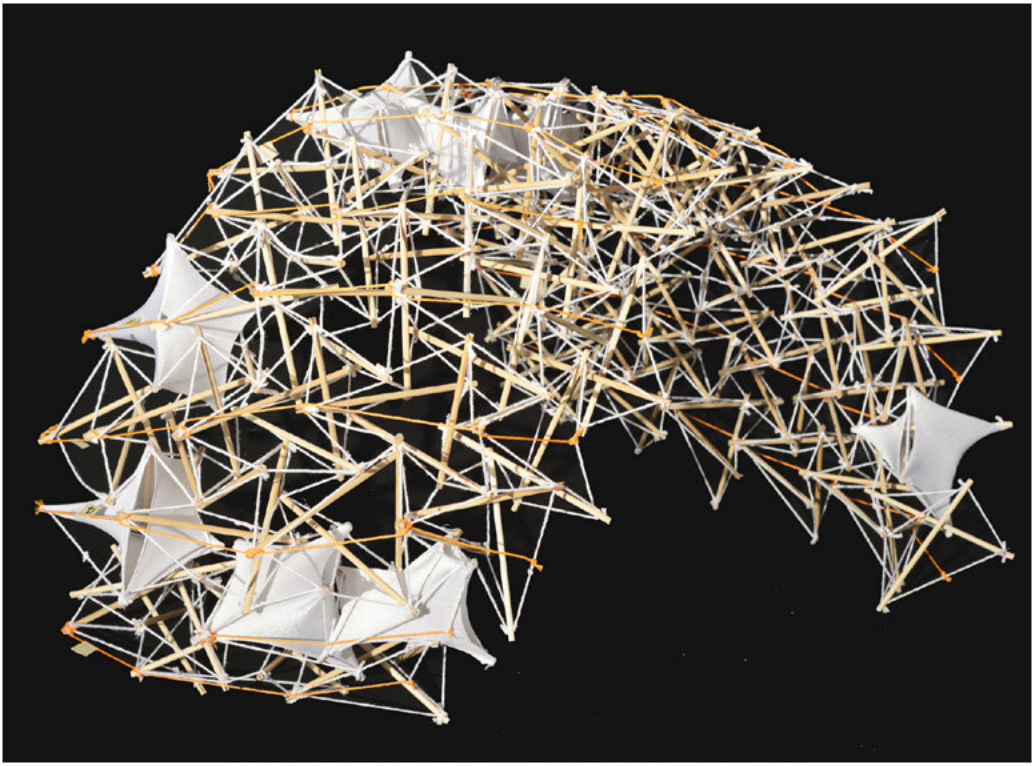

Figure 4. Physical study model of pavilion.

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a result, the fabric enclosed the struts within a minimal volume defined by the elastic qualities of the fabric.

Elastane, a stretchable environmentally friendly 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 utilising a 1/1-scale module prototype. Having studied the elastic behavior of the material, the team 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 minimised 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.

With the successful completion of the *Underwood Pavilion*, the authors envision the next steps for further development moving towards (1) the creation of more complex formal solutions through the utilisation of new module and aggregation variables; (2) the elimination of tensile cables through the introduction of a structural tensile membrane. Although the formal goals are more obvious, the elimination of the tensile cables could have several benefits. In the current configuration, the membrane serves only as a shading device. The use of reinforced tensile membranes could allow for the simplification of the overall structure while simultaneously introducing a more robust, material necessary for larger scale structures. Additionally, the introduction of reinforced fabrics would eliminate the current condition where aluminium and stainless steel interact eliminating long-term problems of fatigue and corrosion. In part, these principals were tested recently in the Noda Pavilion by Prof. Kazuhiro Kojima and his students from the Tokyo University of Science. This pavilion was constructed from a single sheet of fabric. Also, developing the *Underwood Pavilion* further in this direction would create a novel outcome. Rather than building a pavilion from a single sheet of fabric, each module would be developed as an independent tensegrity system. Advantages of that are that such a system would be easier to assemble, expand, modify and change in scale. Using fabric and struts to form a tensegrity module would be a new type of tensegrity structure.

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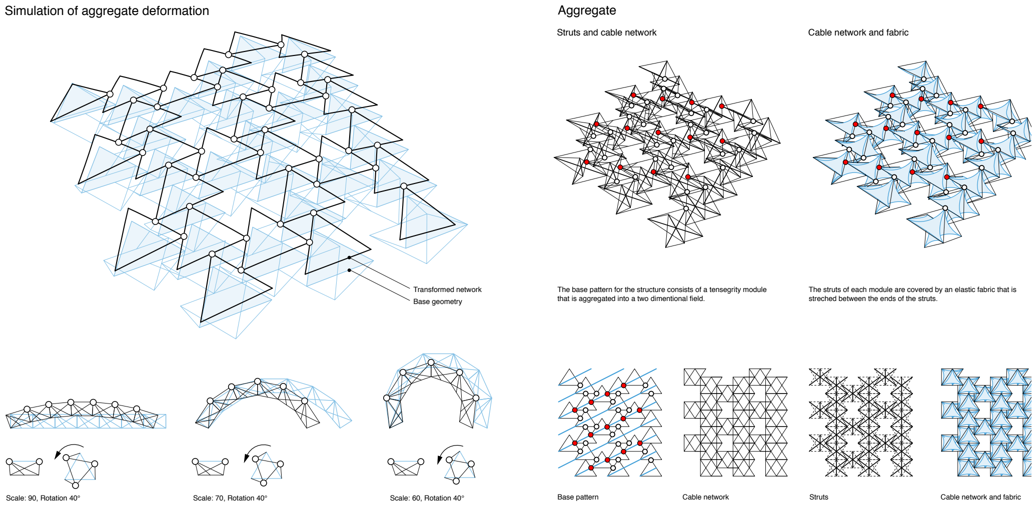

Figure 5. Schematic of the simulation algorithm for one iteration step Figure 5. Aggregation of different module variations.

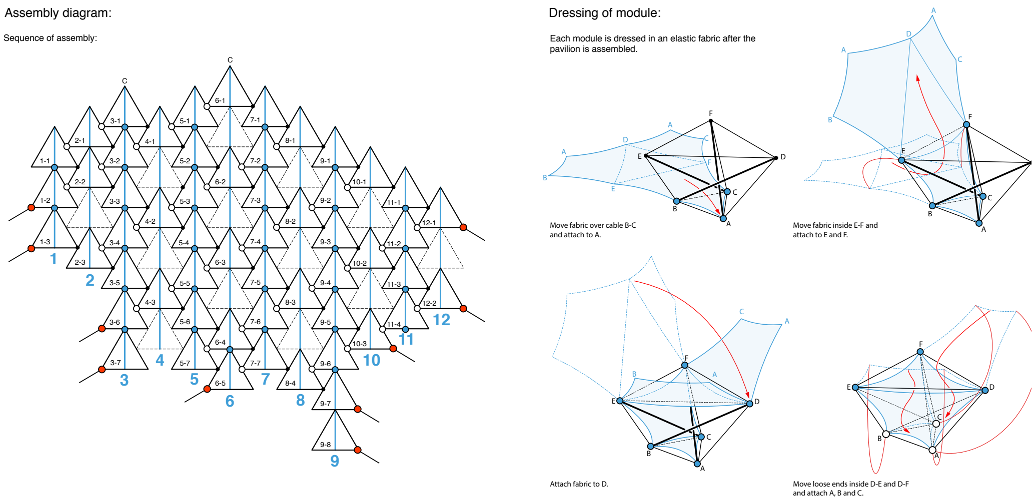

Figure 6. Assembly diagrams.

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8. Findings

Rather than rationalising a given geometry such as a line or sphere into a tensegrity system, the intention of this project was to use simulation tools for a form-finding process. The form in such a process emerges from changing the module's proportion or the configuration of the pattern causing a twisting and bending in the aggregate which was used to define the pavilion's spatial enclosure.

Enclosing the module with an elastic fabric created a unique perception of the structural system. Appearing as volumes that visually do not touch each other created a perception of weightlessness, architecturally articulating a tensegrity system in a new way. Enclosing the modules with a fabric also suggests using the fabric structurally. This would create a novel method of constructing modular based tensegrity structures.

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 behavior along with its ease and range of adapting its geometry. The creation of simplistic and precise details within the pavilion allowed for a fast and accurate assembly process, while also maintaining the possibility of collapsing a mobile pavilion into lightweight bundles of cables and rods for easy transportation. The findings will allow for further prototypes to explore the possibility of more irregular tensegrity systems that respond to new sets of parameters in the future.

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