BeTA PAVILION

CNC Knitted Textile Performance for a Bending-Active Biotensegrity Assembly

Background for the project

BeTA Pavilion (Fig. 1), a Bending-Active Biotensegrity Textile Assembly, is an installation developed by a team of designers, researchers, and students from Kent State University for the 2019 International Association for Shell and Spatial Structures (IASS) Form & Force Expo, organized by Working Group 21: Advanced Manufacturing and Materials. The pavilion tested the dynamic formal opportunities of biotensegrity logics through a material assembly composed of elastically bent glass fiber reinforced plastic (GFRP) and Computer Numerical Control (CNC) knitted textiles. Inspired by animal vertebrae typologies, the structure was assembled with a set of 45 pre-stressed and self-stabilized tetrahedron modules arrayed to achieve structural equilibrium with a range of dynamic motion. The global geometry of the 2mx2mx1.6m form-active structure was developed to respond to local changes in external forces carried by a network of bespoke CNC knitted fabric pieces. The adaptive structure reacts to human touch through kinetic movement while remaining structural stable and retaining efficient curvature and form. This article is developed based on a previous paper by the authors (Davis-Sikora et al, 2020), but with discussions highlighting the performance of CNC knitted textiles.

Design concept

Many novel structural forms with complex curved geometries are derived through experimentations in form and force equilibria. Form-finding methods championed by such figures as Antoni Gaudi, Heinz Isler and Frei Otto leveraged material testing to visualize physical laws that led to new paradigms of structural thinking for complex force distribution systems (Boller and Schwartz, 2020). As a network of precisely balanced components, tensegrity structures rely on form-finding methods to accurately predict states of self-equilibrium across a range of topological conditions. First built by Kenneth Snelson, with the term coined by Buckmininster Fuller, tensegrity structures are composed of isolated compression members braced by a continuous tensioning network.


1a

They are considered a highly efficient resilient system due to their high strength-to-weight ratios, stability and efficacy with minimal structural elements.


1b

Their rapid deployability and controlled pre-tensioning ('tunability') offers a robust typology that has been adopted by a variety of disciplinary fields from biology to cellular mechanics. Tensegrity logics have launched new paradigms of understanding in biomechanical movement and kinematic "living" structures with a capacity of shape adaptability.

The BeTA pavilion installation adopts the logics of functional anatomy and self-organization fundamental to biotensegrity principles based on Kenneth Snelson's and Buckminster Fuller's tensegrity paradigm. Conceived by Dr. Stephen M Levin M.D. in the 1970s, biotensegrity describes an organizing, biological principle of locomotion characterized by a complex interconnected network of tension and compression elements arranged to resist physical forces.

Biotensegrity systems are dynamic and lightweight structures that formally adapt to achieve continued states of equilibrium. Shape adjusting features were instrumental to the BeTA pavilion design. A bending-active system was adopted for the installation to showcase the pavilion's biotensegrity assembly as a passively stable structure. The pairing of bending-active GFRP rods modules with tensioned CNC knitted textile connections produced a reverberant structure when touched.
Forty-five elastically bent regular tetrahedral modules with ten distinct sizes were scaled and sequentially arranged in one chain to describe a hyperbolic paraboloid geometry for the pavilion. Each self-similar tetrahedron module was connected to its adjoining neighbor by an accompanying CNC custom knitted textile. The initial geometry of the pavilion was developed computationally using Rhino/Grasshopper/Kangaroo^{2}®, and its structural performance verified through the continual interplay between physical and computational form-finding. Rhino/Grasshopper/Kiwi!3D interface enabled the integration of isogeometric finite element analysis into a computer aided design

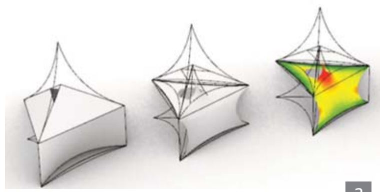
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Figure 1. BeTA Pavilion
Figure 2. Computational Form-finding using Kiwi!3D

environment to 'visualize' the stress distributions in the textiles (Fig. 2) (Kiendl, 2010; Breitenberger, 2016; Bauer, et al, 2017; Davis-Sikora et al, 2020). This process pinpointed the highest stress distribution at the top vertex of the bottom tetrahedron, and a relatively high tensile stress distribution in the middle portion of the fabric, as well as a high tensile stress distribution around the opening. Default material values of GFRP rods and ethylene tetrafluoroethylene as membrane were used to create the digital model, and to find the deformed geometry of the proposed form-active hybrid system. Actual material performance data (i.e., modulus of elasticity, tensile strength, and stress-strain curve for non-linear analysis) could be used to more accurately simulate the force-form relationships of the proposed design.

Large GFRP tetrahedrons arranged at the bottom of the pavilion were each fabricated with six single rods measuring 46cm to 76cm in length, and 0.3175cm in diameter. Three rods were connected at each corner vertex by a 3D printed plastic connector to produce a tetrahedron shape. Flexible GFRP rods with a diameter of 0.1575cm, and a length between 30.5cm and 38cm were used to construct smaller modules with the desired curvature and shape. To accommodate the reduced stiffness, three rods were bundled together and secured at their vertices and mid-points using the connectors shown in Figure 3.

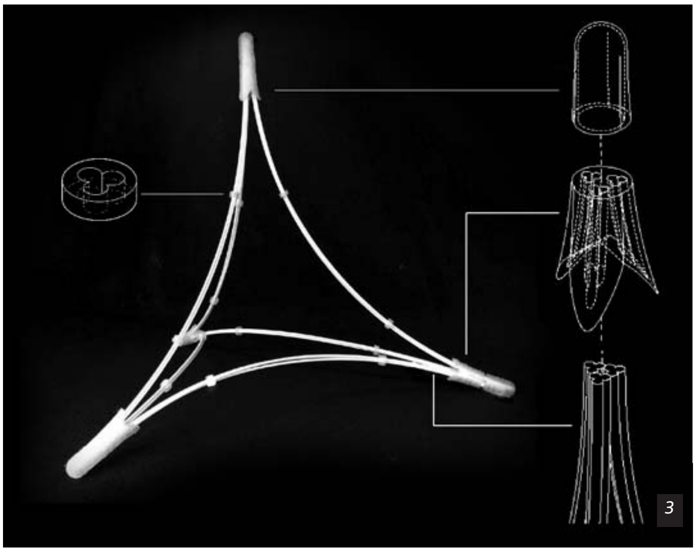
CNC knitted textiles were pretensioned to link the 45 bending-active tetrahedron modules into a continuous chain. Tensioning for each textile was then later adjusted to achieve the pavilion's target geometry. The textile design and patterning were crucial to the project's structural performance and dynamic motion.

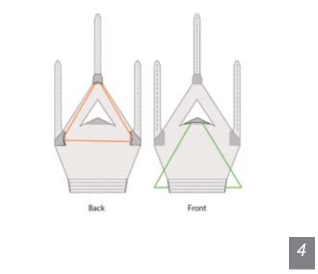
CNC KNITTED TEXTILE

The textile serves as the "soft tissue". It carries tension, connects each tetrahedron 'vertebrae', and makes it possible to form a chain like that of the human spine. Each textile piece incorporated: 1) four fabric pockets, 2) three bottom ribbed tubes, and 3) three knitted bands to connect each tetrahedron with its adjacent neighbors. The knitting pattern shown in Figure 4 was programmed using M1PLUS® software[1]. The platform provides a variety of ready-to-use Knit and Wear modules, as well as flexible programming to adjust and optimize knitting patterns according to customized specifications. All textiles were knitted using polyester air covered spandex yarn on a Stoll CMS 530 HP, 7.2-gauge industrial knitting machine (Fig. 5). The knitting pattern file was developed as a 14-gauge knit with seven fields of intarsia knitting, which used 10 yarn carriers with two ends of air covered spandex consisting of 20 denier spandex core with one ply of 150 denier textured polyester.

Knitting details are illustrated in Figure 6. A total of five different knit structures were designed on each piece of textile. Twenty-two different sizes of textiles were knitted, ranging from 160 stitches wide x 282 stitches long to 284 stitches wide x 752 stitches long, to connect ten different tetrahedron sizes.

An interlock stitch (1) was used to create a strong fabric with knitted slits, through which adjacent bands were looped into a chain. Since a high tension was to be carried by the fabric (2), a tubular pointelle (a double-layered knit), was selected for the main portion of the textile. Four open-ended tubular sections (3) were designed at the bottom of the piece to sleeve GFRP rods through and connect the tetrahedron edge to the textile. The 4 tube design provided options for variable lengths to adjust the tension placed on the fabric. Pockets (4) and (5) were knitted with an interlock jersey structure to provide additional strength at the three tetrahedrons end point connections. The stretched textile, in Figure 7, indicates the high-





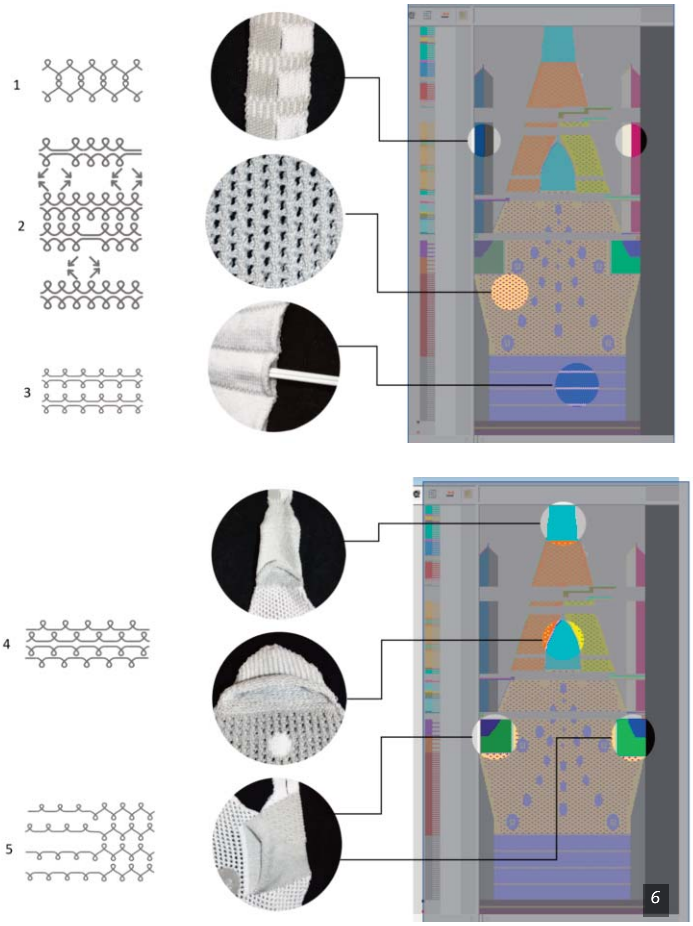


Figure 3. 3D Printed Connectors at the Vertex Connors of Small Tetrahedron
Figure 4. Textile Knitting Pattern
Figure 5. Stoll CMS 530 HP knitting machine
Figure 6. Details of Knitting

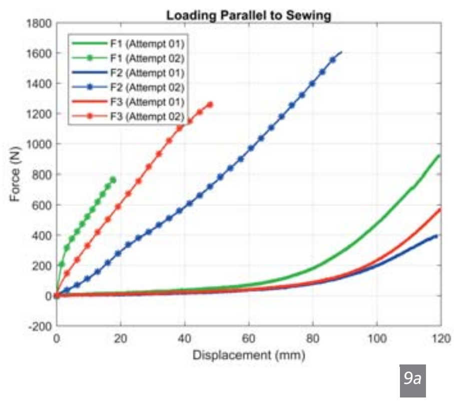
[1] www.stoll.com/M1PLUS

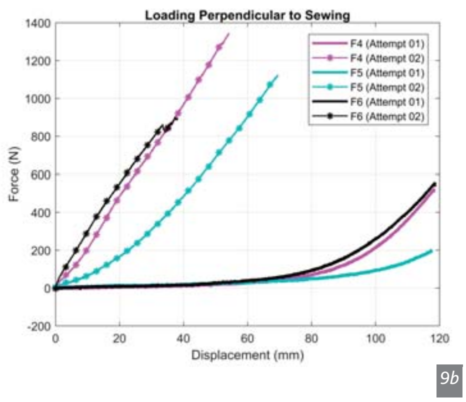
est tensile stress at the vertices. The interlock jersey structure at the knitted pocket carries sufficient tensile capacity to support the stress concentration at this end point.

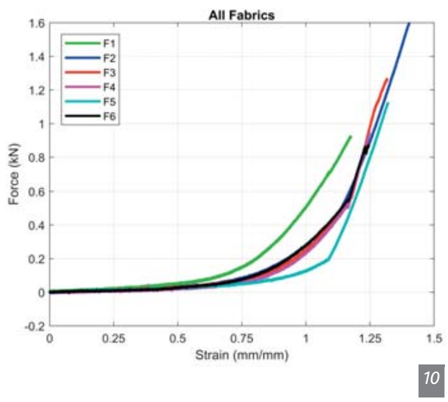
Structural performance of the CNC Knitted fabric

To better understand the structural behavior of the knitted fabric, uniaxial testing with loading parallel and perpendicular to the knitting, respectively, were completed for the CNC knitted textile with a gauge width and length of 10cm. The textile pieces were placed in an MTS universal servohydraulic testing machine equipped with a load cell and data acquisition system (Fig. 8). A total of six pieces were tested with three (F1, F2, and F3) loaded in the direction parallel to the knitting, and three (F4, F5, and F6) loaded in the direction perpendicular to the knitting. The load versus machine stroke results are shown in Figure 9. For each sample two tests were performed. The attempt 1 loading for each textile was to stretch the piece with an elongation of 12cm, which corresponds to the maximum displacement (stroke) of the machine head. After unloading, the piece was released from the jaws of the machine head, and the cross-head was moved upward. The same piece was gripped again by the jaws and the position of the machine head adjusted to consider the permanent deformation of the fabric after the first attempt. The new initial length was recorded for each sample. Pieces were loaded in tension again in attempt 2 until tensile rupture occurred as shown in Figure 8 (b). The testing data was recorded for both attempts for each piece, as shown in Figure 9. The ultimate capacity of each sample is defined as the addition of tensions applied in the two attempts. Samples F1, F2, and F3 had an ultimate load capacity in the range of 1,700N and 2,000N, and a maximum elongation in the second attempt between 2 and 8 cm. The other three had an ultimate load capacity in the direction perpendicular to the knitting ranging between 1,400N and 1,900N, and an ultimate

Figure 7. Stretched Textile
Figure 8. Tensile Testing for the double-layered textile
/a. Tensile Testing
/b. Rupture of the Textile
Figure 9 a/b. Force versus machine stroke for each attempt of the tensile tests
Figure 10. Force versus strain responses







elongation in the range of 4cm and 7cm in the second attempt. The preliminary testing indicates the CNC knitted textiles exhibited similar structural performances in both directions. The preliminary testing results in attempt 1 loading indicate nonlinear inelastic behavior of the textile under a low level of forces, which suggests that the textile is very stretchy, (i.e., the textile filaments tend to stretch while losing the original weaved shape), and the deformation of the textile is not linearly proportional to the tension applied. In addition, large residual stretches were observed after unloading at the end of the fist loading attempt. This phenomenon may be due to the combination of the material and knitting pattern. The polyester spandex yarn may be still in the elastic range under the loading, however slippage of the yarn in the knitted fabric occurred during the loading to generate the residual deformation due to tension. Preliminary testing results indicate the textile exhibited similar mechanical performances in the direction either parallel or perpendicular to the knitting. Additional systematic investigations are required to understand the relationship between material, knitting pattern and mechanical properties. This information would then be used for a more accurate computational form-finding to predict geometric deformations of the stretched textile.

Textile strain was determined by dividing the machine stroke by the initial length between the gripping jaws for each attempt. The strain was then used to combine the response of the two attempts as shown in Figure 10. The two curves from the same sample were combined by overlapping the portion of the two responses for which the load range was the same. It can be noted that when attempts were combined, the force versus strain responses for textiles tested in both directions were consistent. Two branches can be identified. The first branch exhibits a nonlinear trend corresponding to the stretching of the textile. The second branch, most likely, corresponds to the full mechanical engagement of the fibers in tension. The slope of the second branch is consistent among all samples, which suggests that the modulus of elasticity in the two directions is very similar.

As shown in Figure 2, the tensile stress distribution in the textile is not uniform, which was reflected in Figure 7 with large openings or holes in the areas with higher stress and strain. With residual deformation under the low level of stress, the stretch in the CNC knitted fabric still exhibited a linear but non-elastic behavior with the higher level of tensile force applied as shown in Figure 9. The level of tension in the textile not only influences the overall geometry of the pavilion, but also affects the stiffness of the structure. Higher tension generates a stiffer structure with a higher frequency of vibration. Because of the lightweight nature of the assembly, textiles for the bottom tetrahedrons required higher tension (and stiffness) to erect the form-active, hybrid structure.

Conclusion and future research

The construction of an adaptive, hybrid biotensegrity structure, is the first step in an ongoing probe into the complex dynamics of compliant form-active systems. The CNC knitted textile exhibited revealing structural behaviors under the uniaxial loading conditions including non-linear behavior and residual deformation under the low stress levels, and linear but non-elastic behaviors under the high stress conditions. The structural behaviors are similar in the directions parallel and perpendicular to the knit.

BeTA pavilion was assembled multiple times with the same materials. Because of the residual deformation in the textiles under a low level of stress, the global geometry of each assembly appeared different. Slight variations in localized tensioning during each process of assembly produced morphological variations of the target shape. A 'smart' system could be integrated in future projects to monitor strain levels in the knitted fabric; access creep behavior under a long-term loading on the textile; and confirm deviations from the intended shape. Future applications would also benefit from an integrated assessment of elasticity and tension levels produced through the paired performance of GFRP rods and CNC knit fabric. The knit textile embodies a range of performative attributes that drive tensile capacities including yarn type, knit structure, and CNC knit processes (i.e., yarn ends per inch, the tension with which the yarn was knitted, and textile direction in relation to stretch). Moving forward, additional physical and computational modeling of scaled, CNC textile samples targeting selected performance criteria will enable extended testing for long-term and multiple installation efforts.

Acknowledgements

The authors would like to acknowledge the financial support provided by the University Research Council, College of Architecture and Environmental Design, and School of Fashion at Kent State University. Our thanks are also given to TechSyleLAB at Kent State, InnovaKnits North Carolina, and Structure/Material Testing lab at the Case Western Reserve University for equipment/facility support, and the following students from Kent State University, who participated in the fabrication of BeTA Pavilion: Fred Wolfe, Haley DeRose, and Maame Amoah.

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