SOFTENING THE HABITATS
SUSTAINABLE INNOVATION IN MINIMAL MASS STRUCTURES AND LIGHTWEIGHT ARCHITECTURES

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Integration of form-finding, analysis process and production of a bending-active textile hybrid into one model

Rens VORSTERMANS*, Jasper VAN WIJK[a], Patrick TEUFFEL[b], Arjan HABRAKEN[b], Rogier HOUTMAN[a]

*Tentech BV, Rotsoord 9A, NL-13523CL Utrecht, Netherlands, rens@tentech.nl
[a] Tentech BV, Rotsoord 9A, NL-13523CL Utrecht, Netherlands
[b] Eindhoven University of Technology, P.O. box 513, 5600 MB Eindhoven, Netherlands

Abstract

The goal of this research is integrating the form-finding, analysis process and production of bending-active textile hybrids (BATH) into one model, in these systems bending-active elements are combined with membrane elements. For this project Easy FSCB is used which is a software package for the engineering of membrane structures. The simultaneous form-finding approach is used which is described by Lienhard (Lienhard, 2014). Here first the bending-active element is form-found, followed by the coupled form-finding process of the membrane. Now the membrane is attached to the bending-active element in the form-finding process. To simulate the bending-active behavior in Easy FSCB, the Local Coordinate System of each beam link is manually adjusted. Here the initially straight configuration of the bending-active element is implemented. In fact, the beam links want to reset to its initial straight configuration but are attached to the membrane. In the next step the calculation of the hybrid system is executed. Here the Force-density method is used to form-find the membrane according to the deformation of the bending-active element. For validating purposes, a scale model is constructed. In fact, a prototype of the workflow described in this project. The already determined routines of Easy are used in producing the prototype including cutting patterning, compensating and plotting.

Keywords: Active Bending (softening), form-finding, statical analysis, integration, production process, installation sequence

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1. Introduction

Lightweight structures have never been more contemporary and necessary than today. Especially temporary lightweight structures are more and more used in the current built environment. For example, if we compare the number of music or big sports events to that of 25 years ago, it can be concluded that there is an increasing demand for temporary safe structures in this sector. It's the architect's and structural engineer's task to facilitate these structures in the most efficient, aesthetic and safe way. The principles of lightweight engineering are used in combination with the daily developing simulation and analysis tools to reach this goal.

Even more efficient lightweight systems can be constructed while combining the principles of lightweight membrane engineering with bending-active elements. In fact, bending-active elements store bending energy which can be used in pre-stressing, in this case, membrane elements. The need of the bending-active elements to go back to its initial configuration is pre-stressing the membrane elements. Another advantage of building with bending-active elements is that a curved geometry can be achieved by just bending the elements instead of producing actual curved elements. Initial straight or planar elements are used to produce double curved building envelopes.

The goal of this research is integrating the form-finding, analysis process and production of bending-active textile hybrids (BATH) into one model. This model will also contain the information to realize the final model. For this project Easy is used which is a software package for the engineering of membrane structures.

The research on bending-active structures by Julian Lienhard is used as a starting point to construct a workflow on the form-finding process of these hybrid systems. First, the bending-active element is form-found, followed by the coupled form-finding process of the membrane. Here the membrane is attached to the bending-active element in the form-finding process. This will result in an updated membrane geometry according to the deformation of the hybrid system. In fact, both elements in the model are optimized to the behavior of the hybrid system (see BATH by Ahlquist in Figure 1).

Figure 1: SensoryPLAYSCAPE v1.0 (Ahlquist Sean, 2017)

The Local Coordinate System (LCS) of the beam links which are the bending-active elements in the model is reset to an initial straight configuration. In fact, the beam links want to reset to its initial straight configuration but are restrained to the membrane. In the next step, the calculation of the hybrid system is executed. Here the Force-density method is used to form-find the membrane according to the deformation of the bending-active element.

For validating purposes, a scale model is constructed. A prototype of the workflow described in this research to design and construct a bending-active textile hybrid. The already determined routines in Easy are used in producing the prototype including patterning, compensating and plotting. Detailing and determining the building sequence of the prototype also contribute to the relevance of the result of the research.

The workflow presented in this paper can be used in further research of integrating bending-active elements into traditional membrane engineering.

2. Methods

2.1 BATH types

In the last decade just a few bending-active tensile textile hybrids have been built. With every new structure a new combination of words has been used to present the work. Slabbinck introduces a terminology to categorize different types of bending-active tensile hybrids (BATH) (Slabbinck, Suzuki, Solly, Mader, & Knippers, 2017). She states three important requirements to categorize these hybrid systems.

(1) The membrane keeps the bending-active element bent

(2) The buckling strength of the bending-active element is enhanced by the membrane

(3) The membrane is pre-stressed and doubly curved by the bending-active element

In this research a local BATH structure is analyzed. In this type of BATH the bending-active element is coupled by itself (straight element coupled into a ring). The membrane is only deforming the coupled bending active elements into a 3D sculpture.

2.2 Local Coordinate System update (LCS update)

In this research the first step in implementing the bending-active behavior in the model is simulating the Elastica curve within the used software package Easy. The Elastica curve describes a beam's elastic deformation. It was found that manipulating the local coordinate system of beam links would make it possible to set the initially straight configuration of beam elements, in fact resetting the LCS of every beam element. The LCS of one beam element can be defined according to 2 vectors namely the local X direction in global coordinates and the local Y direction in global coordinates. With adjusting the LCS it is possible to implement the initially straight configuration of beam elements in a deformed state.

The Elastica curve simulation can now be explained according to LCS example 1 of Figure 2. A polyline is drawn in external CAD software and imported into Easy. In default the LCS is set along the direction of the beam links. This indicates that nothing will happen when a calculation would have been executed because the beam is already in its initial configuration. It will only deform by its own weight if this is relatively high.

In the second step the LCS is adjusted. The LCS of every beam element is set in the same direction corresponding to an initially straight configuration of the system. The calculation will result in one of the Elastica curves because the beam links will find its shape of maximal bending radius and thus minimal bending moment, within the two pinned supports. If one support would allow sliding over the x-axis the beam will tend to go to its initially straight configuration without any curvature and bending moment.

Next, a new support and 3 cables are added to the model (LCS example 2, Figure 2). The cables are connecting the beam to the new support and thus are restraining the system. When the LCS update is performed and the calculation is executed. It can be seen that the Elastica curve is restrained by the cables and the final result is tending towards the initial design curve. Now the beam again wants to find its way of minimal bending moment but is restrained by cables and 2 pinned supports. A new Elastica curve is found with new boundary conditions. The need of the beam to go back to its initial configuration is now used to tension the cable elements and find a new equilibrium. This simulation will be used in the next steps of the research to implement the bending-active behavior in a hybrid system with membrane elements.

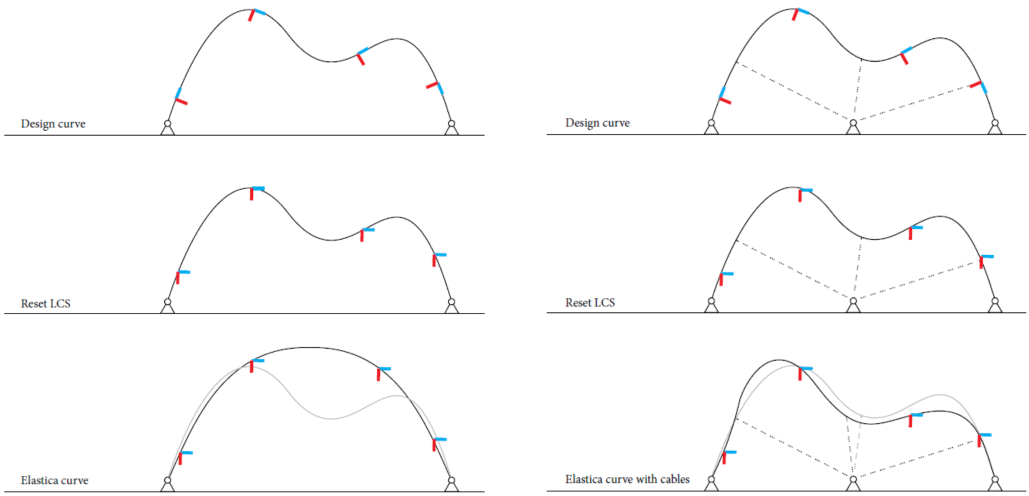

Figure 2: LCS example 1 (left), LCS example 2 (right)

2.3 Successive form-finding approach

“The process is separated into first, the form-finding of an elastically bent beam structure and second, the form-finding of the membrane attached to the beams. Here, the second form-finding step serves to generate an intricate equilibrium system which is based on further deformations in the beam structure.” (Lienhard, 2014)

In the previous section it is elaborated how the initial straight configuration of a beam element can be set to a design curve in Easy. In fact, first the elastically bent beam structure is form-found and the LCS is adjusted to an initial straight configuration. Secondly, the membrane is attached and the form-finding step can be executed using the Force Density Method. Finally, a calculation of the hybrid system is executed. The successive form-finding approach can be explained according to the following steps.

2.3.1 Geometric input

The design curve can be drawn or form-found with external CAD software and imported in Easy as a polyline. Easy translates this DWG file into an Ein-file. This Ein-file consists of point coordinates and defines the link elements. In this case the design curve is form-found with Karamba in Rhino/Grasshopper. Now the initial configuration and the design curve can be used to simulate the bending-active behavior of the beam elements.

2.3.2 Initial configuration

The local coordinate system (LCS) update is used to implement the bending-active behaviour in the calculation of the hybrid system. For the LCS update it is required to determine the initial configuration of the model.

2.3.3 Form-edit model

In the Form-edit module of Easy the mesh settings are set for the first form-finding step of the membrane. In the Form-edit model the mesh boundary and the geometry boundary can be defined separately. In other words, the fixed points of the form-finding procedure can be defined separate from the projected mesh. In the form-finding step the projected mesh will be form-found towards the fixed points of the geometry. In Figure 3 an overview is shown of the Form-edit model.

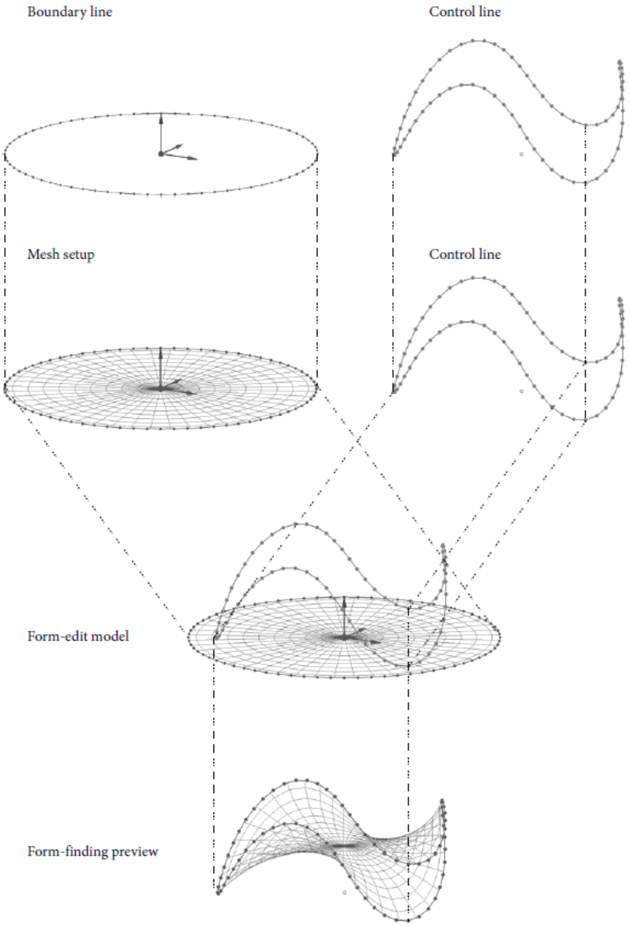

Figure 3: Form-edit model

2.3.4 Form-finding

The form-finding calculation of the membrane is executed in Easy. The Force-Density Method is used in this form-finding calculation.

The result of the form-finding calculation is again an Ein-file which contains the coordinates of the free points after the form-finding step. With these coordinates the link lengths and the new width of every link in the mesh can be calculated. This recalculation of the mesh width is needed to obtain realistic membrane stresses. The width is changed because the mesh is changed from a 2D configuration to a 3D configuration. The width of the membrane elements is calculated with a polygon file which defines polygon elements in between the points of the net.

2.3.5 Easy Beam

The calculation of the hybrid system will be executed in two different Easy Beam models. Here the form-finding result of the membrane is combined with the bending-active simulation of the beam links.

Easy Beam model (1)

In this model the membrane links can still change in length with the use of the Force Density Method. The membrane links are not translated into elastic elements but are still force-density links. Here the membrane geometry can still change according to the deformation of the bending-active element. This results in a membrane geometry which is updated according to the deformation of the beam.

Easy Beam model (2)

From the result of Easy Beam model (1) the unstressed lengths for the membrane elements in Easy Beam model (2) can be calculated.

Now the final calculation is executed with updated membrane geometry and material properties for beam and membrane element.

3. Prototype

3.1 Prototype properties

The global dimensions of the prototype are presented in the Figure 4. The membrane of the prototype is produced at Buitink Technology. The membrane consists of 12 patterns. The stiffness parameters for the used flexible membrane are 11.95 / 15.59 kN/m (warp/weft). These stiffness parameters are used to compensate the cutting patterns.

In the structural model a Young's modulus of 45 GPa is used for the material properties of the GFRP rod. The resulting geometry of the simulation model is checked on bending. The strain by bending is calculated with the height of the profile and its radius (1) where the maximal strain of the material is assumed to be 1.5%.

$$\epsilon = \frac{h}{2 \cdot R} = \frac{10}{2 \cdot 660} = 0.75\% \qquad (1)$$

The minimal radius of the geometry results in the highest strain of the outer fiber, here a radius of 660mm in the model results in a strain of 0.75% with a profile with a height of 10mm. It can be concluded that is it is safe to bent the 10mm rods into the desired radius.

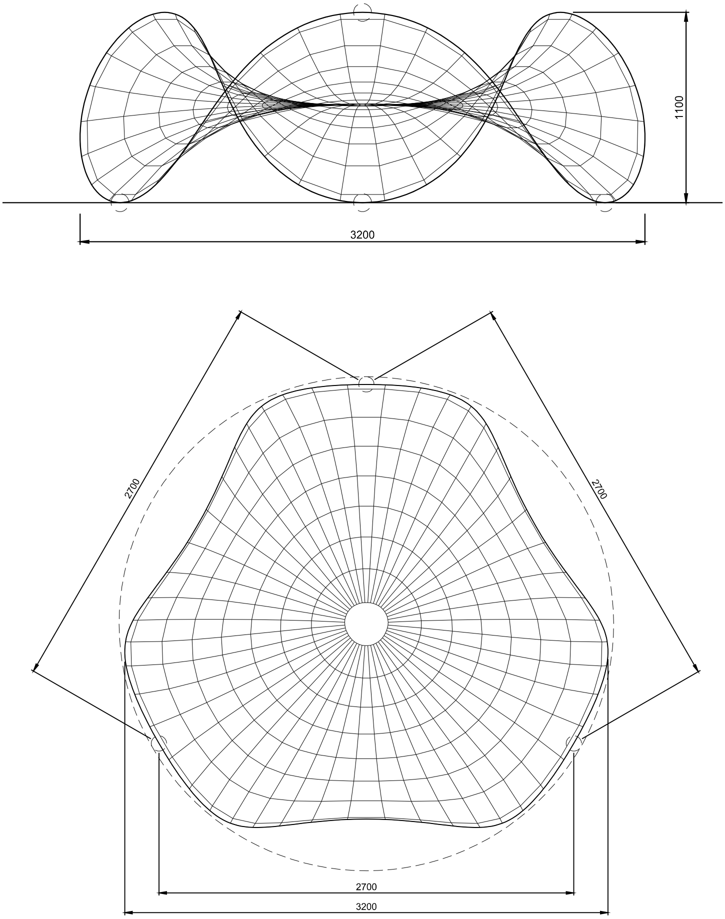

Figure 4: Dimensions of the prototype

3.1 Computational model

The model for the prototype is constructed according to the same procedure as described in the successive form-finding method. The design curve is scaled uniformly towards a total circumference of 12m. This 12m can be divided into 6 equal lengths of 2m. The material properties for the bending-active element are set according to the results of the bending test and consultation with the composite engineer (E = 45 GPa). The cross section of the bending-active element in the Easy Beam model is constructed out of 3 GFRP (glass-fibre-reinforced-polymers) profiles with a diameter of 10mm.

From the Easy Beam model which is calculated with 3 profiles of diameter 10mm the membrane stresses can be extracted. These membrane stresses will be used in compensating the cutting patterns of the membrane. The cutting patterns must be compensated with the strains (Figure 5) calculated from the membrane stresses. This is required because the cutting patterns are generated from the geometry of the stretched membrane.

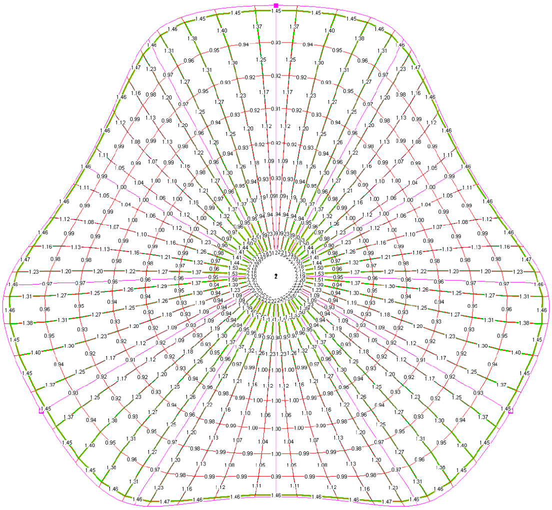

Figure 5: Membrane strains from hybrid calculation

3.2 Building sequence

The setting up of the tent is described by means of several steps. These steps are important to evenly distribute the forces in the membrane and deform the GFRP element into the 3D curve. The prototype is setup within 30 minutes with one person and 3 ground anchors. Wooden slats are used to determine the locations of the ground anchors. In order to setup the tent with one person these anchors are used to connect the GFRP ring to the low points of the tent, this is shown in Figure 6. (The membrane production and test setup is executed at Buitink Technology)

Figure 6: GFRP rings with 3 ground anchors (left), GFRP rings connected to ground anchors (right)

Figure 7: Connect low points to high points in steps

In Figure 7, it is shown that first the high and low points of the membrane are connected to the GFRP element. Thereafter the remaining points of the membrane are connected to the GFRP ring to evenly pre-stress the membrane and deform the GFRP element.

Figure 8: Prototype side view (1)

3.3 Prototype analysis

In the final computational model no horizontal supports are required to stabilize the full system. The low points of the system are free to slide and will find equilibrium with the membrane. In fact, this is required because the bending-active element must find equilibrium with the membrane and concentration of forces at fixed points must be prevented.

In contrast to the Easy Beam model, the prototype model requires the horizontal supports (anchors) to maintain in the current equilibrium state. It is measured that a force of 6kg is required in the direction of the membrane towards the common middle point to keep this shape.

It can be concluded from the test setup that there is significant stress in the membrane. The forces transferred by the S-hooks (connecting membrane to GFRP ring) corresponds to the forces in the Easy Beam model which indicate that the stresses in the membrane will correspond to the stresses in the Easy Beam model. In Table 1, the prototype is compared with the Easy Beam model. Here the high and midpoint of the models are compared. The comparison of geometry can be improved by performing it with a 3D scanner.

Table 1: Comparison of Easy Beam model with the prototype

Comparison	**Easy Beam**	**Prototype**
High point [mm]	1058	1050
Midpoint [mm]	543	550
Force in S-hooks [kN]	0.059	0.055

4. Conclusions

It can be concluded that simulating the Elastica curve and thus the bending-active behavior in beam elements with the LCS update can used in the design and form-finding process of bending-active textile hybrids. In this research it is used within the software package Easy and combined with membrane form-finding using the force-density method.

In the Easy Beam model exact equilibrium is found between the bending-active element and the membrane. Because the prototype shows instability problems without horizontal supports at the low points it can be concluded that realizing this exact equilibrium in the prototype is very sensitive to inaccuracies in the stiffness parameters of the bending-active or membrane elements.

The use of a membrane material with higher stiffness parameters could possibly increase the stability of the model but this leads to a decrease of compensation values which increases the influence of inaccuracies in the production process.

An additional attention point of the required anchors points is that shear forces will concentrate at the connection of the GFRP ring to the anchor. Here the ring is loaded perpendicular to the direction of the glass fibre orientation. The shear capacity of these pultruded profiles is limited in this direction. It is thus very important to limit the peak forces and locate the anchors at the right position if they are required to keep the desired shape.

Throughout this project one design curve is used for constructing the workflow of the form-finding, calculation and realization model. In further research it would be interesting to start a new project with a design analysis on physical models. In this way different types of bending-active textile hybrids can be modelled and the use of the workflow of this research can be extended.

Figure 9: Prototype front view at night (1)

Figure 10: Prototype top view at night (2)

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