Bending incorporated: designing tension structures by integrating bending-active elements

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Abstract

By integrating elastically bent, linear elements, a supporting system for membrane structures is created that provides more freedom in design and can reduce the required amount of external supports. To fully explore the potential and possibilities of shaping tension structures by integrating these bending-active elements, the authors developed an easy-to-use design tool for fast, robust and flexible modelling and form finding. This paper presents the tool through a series of case studies that go beyond previously presented applications.

Keywords: bending-active structure, tension structure, form finding, design tool

1 Introduction

Doubly curved membrane structures are typically tensioned between high and low anchor points, attached to the ground, buildings or poles. By integrating elastically bent, linear elements in the membrane surface, an internal supporting and shape-defining system is created that provides more freedom in design and reduces the required amount of external supports.

These elastically bent elements are often referred to as ‘spline’ or ‘bending-active’ elements. The latter term was introduced by Knippers et al. to describe “curved beam or surface structures that base their geometry on the elastic deformation of initially straight or planar elements" [1,2]. Combining bending-active elements with a membrane structure creates a hybrid construction with interacting components. The 'igloo' camping tent or the umbrella are probably the best-known examples of this kind of structural system.

Currently, an integrated tool for form finding of bending-active tension structures in which the interaction between tension and bending elements can be properly modelled and calculated is not available. Therefore, the authors developed a design tool with a flexible and easy-to-use graphical interface that allows the potential of bending-active elements for shaping tension structures to be fully explored.

2 Interactive form finding

The presented tool is written in Python [3] and implemented in Rhinoceros [4], providing a familiar and comprehensive user interface. Building upon the framework for form finding of tension structures using discrete networks, developed by Veenendaal and Block [5], the equilibrium problem of the hybrid system, using a mixed force density formulation, is solved with the dynamic relaxation. Results can be easily visualised and inspected in the Rhinoceros 3D model space.

Using a mixed formulation, the force density of each element of the system is controlled interactively by the user by assigning a force, length, force density, or stiffness to the element, or any combination of these properties. Both the boundary conditions and the form finding parameters can be changed in between calculation runs to interactively steer the design in the desired direction.

As an example, Figures 1 to 3 show different stages of a design exploration starting from a simple arch-supported membrane (Figure 1) similar to the one presented in [6]. By releasing one end of the pinned arch and fixing the other (by defining a starting angle), the bent element straightens and becomes a cantilever. Additionally, half of the fixed boundary nodes of the net are released and the force densities of the elements between those nodes increased to create boundary cables. Figures 2 and 3 illustrate the input and shape of equilibrium, respectively.

Figure 1. Perspective and side view of the arch-supported membrane structure.

Figure 2. Input of the cantilever structure: one fixed end (left), defined by fixing the last two nodes of the bending element, and one free end (right); released boundary nodes for boundary cables to the right.

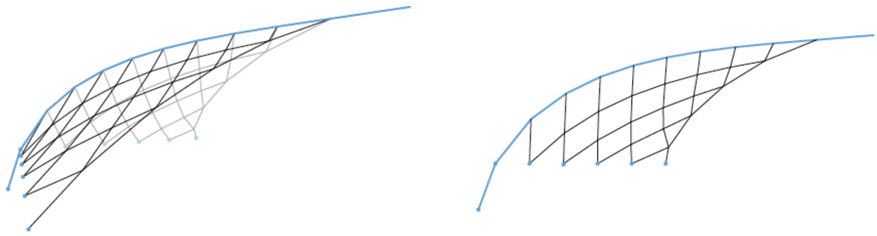

Figure 3. Equilibrium shape of the cantilever structure.

In addition to changing the node fixity and adding or deleting cable-net elements, various attributes of the structural components can be changed during form finding. The user can, for example, decide to make the boundary edges force-controlled, define a set of links as cable and/or change the initial length or section properties of the bending element. The latter is illustrated in the next example.

Three alternatives of the same structure in Figure 3, but with different properties of the bending element are generated. Figure 4a is the reference figure, Figure 4b has a bending element with a Young's modulus that is three times lower, and the bending element of the structure in Figure 4c has a diameter twice as large. It is clear that this form finding tool allows intuitive and fast exploration of the influence of different properties on the equilibrium shapes of the hybrid structure.

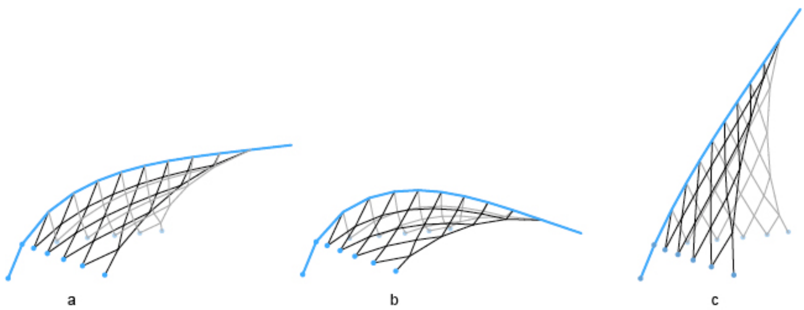

Figure 4. Exploring different equilibrium shapes by changing the attributes of the bending element, with a. the reference figure; b. increasing the bending element's Young's modulus three times; and c. doubling the section of the bending element.

An additional advantage and feature of the tool is the graphical representation of the forces and bending moments. The axial forces in the cable-net links, cables and bending elements are visualised (blue being compression and red tension), as well as the three-dimensional bending moments along the bending elements, reaction forces at the supports and any residual forces during calculation. This information allows the user to evaluate the generated shapes structurally, change some attributes if so desired, and rerun, or continue, the form finding calculation.

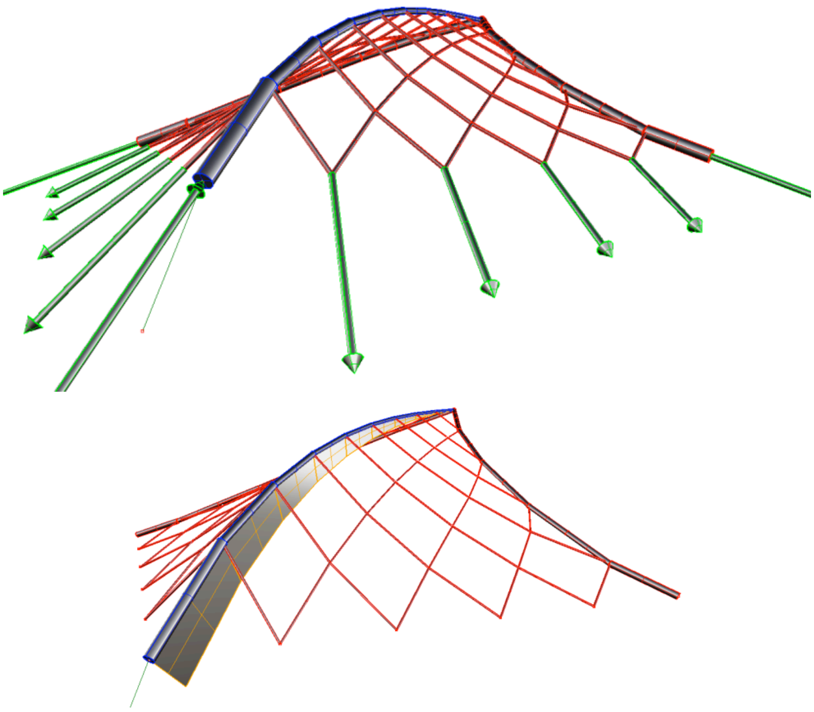

Figure 5. Graphical representation of the axial forces in all elements (red tension, blue compression), reaction forces (upper), and the 3D bending moments in the bending element (lower).

3 Design examples

The potential of integrating bending-active elements in a membrane structure with the design tool is demonstrated with the following two cases. The first is an extension of the cantilevered construction illustrated in Figure 3, and consists of multiple cantilevered bending elements (Figure 6). It clearly shows the supporting and shape-defining function of the elements. The second example is a combination of an elastically bent arch with a 'suspended' bending element (Figure 7).

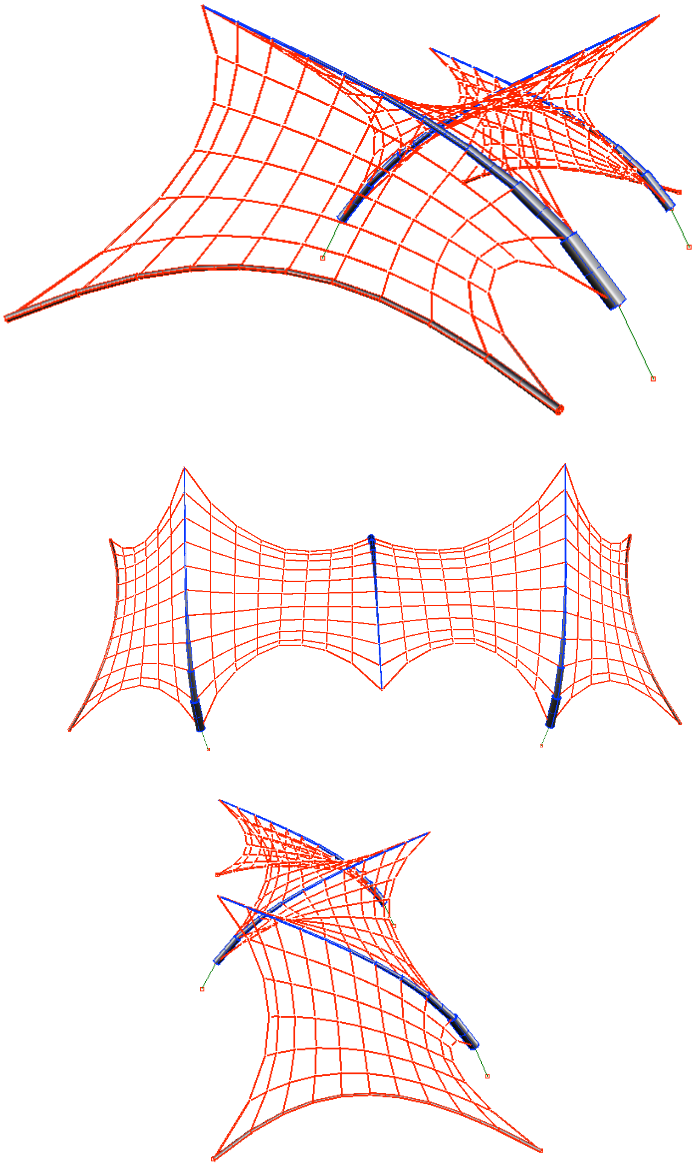

Figure 6. Membrane structure with multiple cantilevered bending elements.

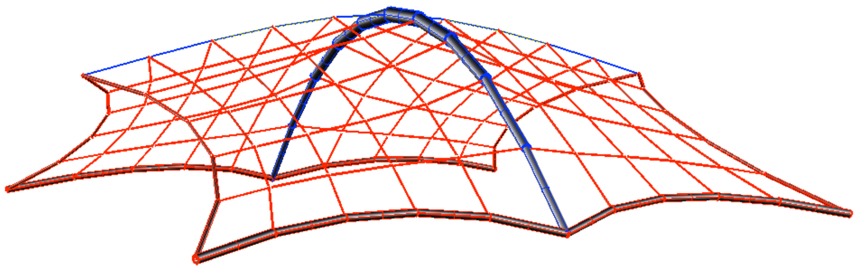

Figure 7. Combination of an elastically bent arch with a 'suspended' bending element.

4 Conclusions

Integrating bending-active elements in tension structures is a powerful and interesting way to support and shape them. Various design configurations and applications of these hybrid constructions are feasible. To allow full exploration of the design possibilities, a form finding tool has been developed and subsequently demonstrated in this paper through a series of case studies.

Future development of the tool will be focused on the use of different solving strategies and the integration of a statical analysis module.

References

[1] KNIPPERS, J., CREMERS, J., GABLER, M., LIENHARD, J., *Construction Manual for Polymers + Membranes*, Institut für internationale Architektur-Dokumentation. München: Edition Detail, 2011.

[2] LIENHARD, J., ALPERMANN H., GENGNAGEL, C., KNIPPERS, J., *Active Bending, a Review on structures where bending is used as a self formation process,* Proceedings of the International IASS Symposium, Seoul, Korea, 2012.

[3] Python Programming Language – www.python.org

[4] Rhinoceros – www.rhino3d.com

[5] VEENDENDAAL, D., BLOCK, P., *An overview and comparison of structural form finding methods for general networks, International Journal of Solids and Structures*, Vol. 49, no. 26, pp. 3741-3753.

[6] ADRIAENSSENS, S., *Feasibility Study of Medium Span Spliced Spline Stressed Membranes*. *International Journal of Space Structures,* Vol. 23, no. 4, 2008, pp. 243-251.