1. Animation tools
Tensegrity structures can be approximated in animation or gaming software using spring systems. By connecting springs to rigid bodies in the correct configuration, it is possible to simulate stress in a system and induce a state of tensional integrity. Although this method has been used effectively by the authors to find the form of basic tensegrity structures, it is tricky to input initial geometry for complex arrangements and to adjust parameters. Furthermore, the nature of the software makes it difficult to be sure that the simulations correspond to precise structural behavior. Some of these complexities can be overcome with scripting/programming and through user-defined equations. Tristan D’Este Sterk and Andrew Payne have carried out cursory research into tensegrity form finding with animation tools.

2. Associative modeling
As mentioned earlier, the form of a tensegrity structure depends not only on its initial geometry but also on a balance of forces between self stressed members. Associative modeling environments typically do not have features to support this, however it is possible to parametrically define the mechanical behavior of a single tensegrity module using a ‘twist angle’. Proliferating the module via a suitable connective logic can generate complex tessellations whose global form can be altered by adjusting various local parameters. An example of this approach can be found in the work of Katherine Liapi who has developed a parametric method to accurately determine the shape of double layer tensegrity networks (Liapi 2001; Liapi and Kim2004). Although promising, there is a need to develop these tools further before they are directly useful for design applications.

3. Force Density Method and Dynamic relaxation
Typically these approaches are primarily explored within engineering research groups. They are developed from traditional methods of finite element analysis and are capable of precise calculations. A good example of integrating FEA tools with design software is RhinoMembrane, a commercial plug-in for Rhinoceros. The latest release (Version 1.22) implements a tensegrity form-finding algorithm based on the force density method. A further example that explores double layer tensegrity grids and integrates dynamic relaxation with associative modeling tools can be found in the work of Gustav Fagerstrom (Fagerstrom 2009).

Although the tools described above are capable of simulating the behavior of tensegrity structures, on the whole they are cumbersome and inadequate for comprehensive design exploration, specifically with regards to 3D compressed components. The first category is probably the most accessible to designers but accuracy is questionable. The second is at a preliminary stage of development and the final category describes deterministic processes that produce a single optimal solution to a given set of constraints. To comprehensively explore the architectural potential of tensegrity structures, a computational method is needed where global geometry can be transformed in real-time by manipulating the properties of local connections between and within modules. Furthermore, structural feedback is needed to determine which parts of the structure are in compression and tension, and to communicate whether a given assembly conforms to a state of tensional integrity.

Particle-Spring Systems: Real Time Form Finding with STRUCK
Particle-spring systems are widely used in computer graphics to produce visually correct interactive animations. Research carried out at MIT into the suitability of particle-spring systems as design tools has demonstrated their usefulness in finding the form of tension structures in a real time environment (Killian and Ochsendorf 2005). The study concludes that particle-spring systems are a particularly powerful way for architects to accurately explore a synthesis of form and structure. In a recent publication, Dr. Thomas Seebohm describes three-dimensional tensegrity structures generated from two-dimensional ‘topologies’ using a novel Java applet named Struck (Seebohm 2008). This software was developed in 1998 by Gerald De Jong specifically to find the form of tensegrity systems (De Jong 1998). There is very little documentation about how Struck actually works, making Seebohm’s work important for understanding some of the mathematical principles behind the interface. From his descriptions is clear that Struck is based on relatively simple particle-spring logic and is sufficiently accurate to enable design exploration of complex tensegrity structures. Struck considers point mass points in 3D space to be connected via elastic springs. Each spring has a desired rest length, when the spring length is greater than the rest length, the particles are pulled towards each other and the spring is compressed. When the spring length is less than the rest length then particles are forced away from each other and the spring is tensed. Struck calculates the stable, self-stressed form of a system given its initial geometry and the desired rest length of each spring. This process is visualized in real time and provides color-coordinated feedback to identify compressed components (red), tensile cables (blue) and redundant structural elements (black). Once a system has reached a stable state, it becomes possible to explore various shape transformations in real-time by using a slider to change the rest lengths of tensile and compressive elements (Figure 5). Global geometry can thus be manipulated by adjusting local structural relationships.

Figure 5 Struck interface showing parameter panels. Struck supports complex tessellations with large numbers of elements such as this double layer tensegrity grid (right – approx. 6500 particles)

Struck is an innovative applet that supports architectural exploration of complex tensegrity structures. It enables real time and interactive structural evaluation and easily handles large numbers of elements. Although Struck is not adequate for full design and engineering resolution, it is an outstanding example of a design environment that extends computation beyond the inert representational realm characterized of standard CAAD tools. Architects are able to transcend the limits of Euclidean space through a synthesis of form and structure. Structural logic can be used to turn a form finding as an ‘optimal’ solution. This approach to design not only initiates early stage interdisciplinary collaboration but also helps to bridge the divide between architectural design conception and construction. It should be noted that Struck is introduced here as a preliminary example of the kind of design tools necessary to comprehensively explore statically indeterminate structures. To enable a fully integrated cross-disciplinary investigation between architecture and engineering teams, additional software components are needed. These components must address material properties (elasticity, gravity, self-weight), external loads, geometric constraints between elements and user-defined boundary constraints.
A Class 2 Pentagonal Tensegrity Tower

A 30 meter tall signage tower is currently being documented for a site in Melbourne, Australia. The tower stands on the perimeter of the CBD, within a site that has been long dormant. It signals the forthcoming development of a new city precinct and invites the public to explore this exciting proposition through a web-based portal. The tower concept was conceived by a branding company together with the site developer. Our team was engaged to "realize" the idea in an interesting and novel way. According to the original brief, the tower is to "look unsteady, like it's under construction". For these reasons, tensegrity seemed to be a practical approach to take.

After a number of esquisse designs, the clients were most taken by the aesthetic achievable with Class 2 structures. These are structures in which unidirectional struts are connected to each other in a linear manner. When they are in a tensegrity configuration, compression elements become discontinuous spirals. The number of spirals can range from three to infinity and a wide variety of tubular forms can be achieved by adjusting the length of tension members. A further important characteristic of class 2 structures is that if the joints between struts are considered fixed, and first level struts are supported on ground, then the whole assembly is statically determinate and can be analyzed using conventional CAE software.

A series of physical models were produced as proof of concept and to initiate discussion with the structural engineer. It was agreed that a pentagonal (five-spiral) structure would be sufficient to create the kind of "unsteady" aesthetic that was desired. A Struck model was then created to explore a variety of potential forms in real-time. Anchor points were added to the Struck model to ensure a planar footing. These can be seen in Figure 6 as black points at the base of the structure. The shape and height of the final structure was fine-tuned in Struck to accommodate the signage and ensure its visual prominence on the city skyline.

Design Examples

A Tensegrity Footbridge with 3D Compressed Components

This project is a speculative design for a footbridge that is not sited and functions purely as a proof of concept. It aims to explore Struck in relation to tensegrity structures. Since Struck is limited to dealing with linear compression struts and pin-joints, it becomes necessary to develop a strategy that prevents 3D components from collapsing. To explore these ideas, a simple 3D compression member was desired that would enable a tube-like configuration. In consultation with engineers it was decided that the most appropriate way of achieving this was to consider the footbridge as a series of non-orthogonal compression rings connected via tension cables. To keep things simple the team developed a four-sided element based on the tetrahedron.

The initial bridge geometry was created in Rhinoceros and is similar to the model pictured on the left of Figure 7. A script was developed to enable interoperability between Rhino and Struck. To prevent each pin-jointed module from collapsing under force, additional compression struts were added to create closed tetrahedron modules. The closed tetrahedrons are mechanically stable and can resist the forces acting to collapse the structure. In Figure 7 the additional compression elements have been hidden to clearly illustrate the intended structure. The compressive forces resisted by the hidden members in the models below become bending and torsion that must be absorbed by rigid joints at each vertex of the final 3D component.

From early physical models we knew that cross-sectional cables govern the length of the bridge structure and axial cables along its four edges determine the "form". Each of the edge cables can be individually controlled with the interactive sliders in Struck. This functionality means the structure can be distorted from a rectilinear tube into a sharply arched form in real time as shown in Figure 7. A comparison between the analytic, digital and physical models in Figure 8 show them to be satisfactorily similar to conclude that particle-spring systems are a useful way for designers to find the form of statically indeterminate assemblies, including tensegrity structures with 3D compression members.

Conclusion

The authors believe that Tensegrity structures are of particular interest to architects and engineers exploring interdisciplinary collaboration and the potential of design tools that synthesize formal and structural requirements. Tensegrity systems express structural clarity by isolating forces within discrete systems of continuous tension and discontinuous compression. It is our experience that this property, and the embedded knowledge it represents, enables clear and coherent discussion between architects and structural consultants. The research presented within this paper explores a further class of tensegrity structures characterized by the use of 3D 'compressed' components. A preliminary discussion outlines why these structures are more interesting and robust than conventional class 1, 2 and 3 tensegrity systems and some basic assemblies are described. An overview of tensegrity form finding with Struck is followed by a description of a design environment that uses particle-spring logic to simulate the behavior of tensegrity structures. Two projects that implement this software within the design process are briefly discussed. The projects confirm Kilian and Ochsendorf's original conclusion about the nascent potential of particle-spring systems in structural evaluation and form "discovery". The research presented here extends this notion to tensegrity structures and demonstrates a mechanism by which architects can engage CAAD environments beyond mere representation.
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This paper presents some preliminary outcomes from an ongoing research project being undertaken at the Royal Melbourne Institute of Technology between the Spatial Information Architecture Laboratory and the Innovative Structures Group. The authors would like to thank Professors Mark Burry and Mike Xie for their guidance and for the opportunity to implement this research within full-scale construction. We would also like to thank Phillip Beesley for his timely nudge in the right direction and without whom access to the late Dr. Thomas Seebohm’s tensility archives would have been impossible.

References


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Abstract

This paper details a series of preliminary explorations into the concept of kinetic tensegrity grids that can respond to stimuli by changing their shape, porosity and transparency. The research presented explores double-layer tensegrity grids that utilize 3D ‘compressed’ components. A case study demonstrates their applicability to the formation of sophisticated building envelopes that can actively or passively respond to changes in the environment. A computational form finding tool is introduced to study design variations in such grids. This tool is shown to expand the design spectrum by supporting increased complexity and revealing unexpected design potential. This research is significant as it outlines a practical methodology for conceiving responsive building systems. In particular it illustrates an approach that synthesizes design concerns with engineering and fabrication goals.

1 Introduction

1.1 Tensility Structures

Tensility is a structural concept that appears to follow fundamental principles of material efficiency and adaptability that permeate the natural world. It is relevant at many scales and has been used to describe the configuration of the universe (Fuller 1975), the physiology of the human body and the structural behavior exhibited by water molecules, proteins, viruses and other biological cells. Of particular appeal to architects and engineers is the fact they consolidate a number of important design, engineering and fabrication concerns. These include stability, functionality, scalability, ornament, structural clarity, efficiency, materiality and form generating potential. Tensility structures are thus fruitful territory for exploring a co-rational approach to design where form is inextricably linked with force and design conception is enhanced with appropriate strategies for design realization.

Tensility structures are particularly interesting when considering the development of responsive systems and have been explored by a number of researchers in a variety of fields. Perhaps most notable within the contemporary architectural domain is Tristan Sterk’s research into actuated tensegrity structures. Of critical significance is the fact tensility structures are lightweight and characterized by a state of “dynamic equilibrium” (Hanaor 1992). Effectively, this means that their shape is dependant upon a combination of topological characteristics, material properties and the amount of pro-stress in tensile elements. Due to the interdependent nature of all elements, a slight change in any of these parameters can result in a significant shape transformation. Rene Metro presents a comprehensive definition of tensility structures and one that specifically covers the novel assemblies described in this paper: “A tensility state is a stable self-equilibrated state of a system containing a discontinuous set of compressed components inside a continuum of tensioned components” (Metro 2002).
We have developed a script for Rhinoceros that extends this process into three dimensions. Initial geometry is generated in Rhinoceros and assigned either tensile or compressive properties using a layer naming convention. Multiple layers can be used to define different rest lengths and properties for different elements. Once the system is activated in Struck, it becomes possible to explore design variations in real time by using a parameter slider to change the rest lengths of tensile and compressive elements. Because all structural elements are inert, global geometry can be manipulated by adjusting local parameters. More detailed information about Struck and an overview of alternate computational tools that can aid in the design of complex tensegrity structures is presented in a recent publication by the authors (Frumar and Zhou 2009).

2 A Case Study – Kinetic Grid 01

2.1 Initial Schematic

Two components previously developed by the authors were noted for their ability to interconnect. When attached in the correct manner they form a tensegrity grid with regular openings. The grid is infinitely extensible in three axes. Initially, the aim of this investigation was to explore a convergence of design and engineering goals by investigating the architectural potential of this particular grid assembly. It was envisioned as a large spanning static building envelope suitable for constructing non-standard architectural geometries. To verify that such an assembly would be self-stressed and stable, a physical model approximately 300 x 300mm was built using interlocking laser cut timber and fishing line (Figure 1).

2.2 Activating the Grid in Struck

Once the stability of the grid assembly was confirmed through the physical model-making process, a digital model was created in Rhinoceros to get a better understanding of what the assembly would look like ‘on masse’. The inert Rhinoceros geometry was used to generate the input data for an active digital model in Struck. The initial geometry and activated assembly are illustrated in Figure 1. Generally speaking, geometry exported from Rhinoceros is not initially active in Struck. Activation is achieved by gradually adjusting the various lengths of members until all members are acting in tension or compression. As mentioned previously, this process changes the color of the geometry from black (meaning structural elements are carrying no load) to red (compressed components) and blue (tensile elements). Importantly, during this procedure it becomes immediately apparent if the assembly is unstable and also if there are any elements that could be removed without compromising the overall integrity of the structure.

Figure 1. 3D components, physical assembly, ‘inert’ Rhinoceros geometry and ‘activated’ assembly in Struck

Kinetic Tensegrity Grids with 3D Compressed Components
Activating the grid geometry in Struck proved particularly rewarding. Despite our initial goal of creating a static building envelope, it became apparent during the initial phases of the ‘tuning’ process, that the grid assembly could be distorted in a number of unexpected ways. Of particular interest was the ability to manipulate openings in the structure. The active digital model enabled us to determine an appropriate means of controlling this movement using a series of extra cables placed in the positions shown in Figure 3. The additional cables create an astonishing effect. The entire structure is able to transform between closed and open states. The transparency and porosity of the assembly can be controlled in real time by adjusting the length of the additional cables. Furthermore, the inclusion of actuated ‘spines’ makes it possible to control the global shape of the structure as illustrated in Figure 1. Significantly, the shape and porosity controllers are independent and can be operated individually or in unison. In a full-scale construction, heat-activated actuators could be used to passively control this movement.

A physical model was built to test the discoveries made in Struck. The model was constructed with rotating joints in the required locations. Figure 3 demonstrates that the physical model operates analogously to its digital counterpart and maintains stability in all positions. With these properties confirmed, an expanded digital model was developed to further explore the potential architectural applicability of the grid structure. The most obvious application is lightweight dynamic façade systems and building envelopes that actively respond to contextual forces by reducing energy loads on and within the built environment (Figure 4).

3 Further Grid Assemblies

Further kinetic grid studies that use 3D compressed components are illustrated in Figure 5 to demonstrate some alternate configurations. To ensure the stability of these assemblies, physical models were used as necessary as Struck was used to carefully ‘tune’ them into shape. Each of the grids is infinitely extensible in at least two axes and has its own structural character, mode of actuation and effect when deployed in large assemblies. A common feature is that shape, porosity and transparency can be controlled with correctly placed actuators and suitable compressed component mechanisms.

Figure 5. Alternate kinetic tensegrity grid configurations

4 Conclusion

The research presented in this paper introduces a methodology for generating a virtually unlimited assortment of kinetic and rigid tensegrity grid structures with 3D components. The use of 3D ‘compressed’ components is shown to increase the design spectrum available to architects wishing to explore tensegrity structures by enlarging the field of potential tessellations and providing more appropriate structural properties than typical tensegrity assemblies.

An innovative Java applet that supports design exploration is introduced. This tool enables real time and interactive structural evaluation of complex tensegrity structures and avoids the need for building physical models in order to verify the stability and means of actuation in kinetic assemblies. Although not adequate for full design and engineering resolution, the Struck applet is an outstanding example of a design-based environment that extends computation beyond the inert representational realm characteristic of standard CAAD tools. It certainly begins to address some of the functionality needed to support early stage design development of responsive building technologies, structures and systems. It is important to note, the behavior of the active digital model in Struck is roughly equivalent to that of small-scale physical models where self-weight is negligible. Full-scale construction of the assemblies presented would require significant software development to enable material properties and structural forces to be accurately determined. Furthermore, practical means of integrating these types of systems with typical building requirements such as waterproofing and harvesting/shedding of rainwater is necessary.
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This paper presents outcomes from an ongoing research project being undertaken at the Royal Melbourne Institute of Technology between the Spatial Information Architecture Laboratory (SIAL) and the Innovative Structures Group (ISG). The authors would like to thank Professors Mark Burry and Mike Xie for their guidance. We would also like to thank Phillip Beesley for his timely nudge in the right direction and without whom access to the late Dr. Thomas Seebohm’s tensegrity archives would have been impossible.

References


