Kinetic Tensegrity Grids with 3D Compressed Components

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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 real time. 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 TENSEGRITY STRUCTURES
Tensegrity is a structural concept that appears to follow the fundamental principles of material efficiency and adaptability found in 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 that tensegrity structures consolidate a number of important design, engineering, and fabrication concerns. These include stability, functionality, scalability, ornament, structural clarity, efficiency, materiality, and form-generating potential. Tensegrity structures are, thus, fruitful territory for exploring a co-rational approach to design, where form is inextricably linked with force, and design conception is enmeshed with appropriate strategies for design realization.

Tensegrity 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 that tensegrity structures are lightweight and characterized by a state of "dynamic equilibrium" (Hanaor 1992). Effectively, this means that their shape is dependent upon a combination of topological characteristics, material properties, and the amount of pre-stress in tensile elements. Due to the interdependent nature of all the elements, a slight change in any of these parameters can result in a significant shape transformation. Engineer, Rene Motro presents a comprehensive definition of tensegrity structures and one that specifically covers the novel assemblies described in this paper: "A tensegrity state is a stable self-equilibrated state of a system containing a discontinuous set of compressed components inside a continuum of tensioned components" (Motro 2002).

1.2 3D COMPONENTS
The majority of research and discourse to date has focused on class 1, 2, and 3 tensegrity structures assembled from tensile cables and linear compressive struts. There are few practical examples where compressed components consist of subassemblies that form geometries that are more complex. Regarding the definition above, Motro explicitly notes, "the shape of the 'compressed components' is not prescribed to be linear, surface or volume type." In a concurrent publication, the authors of this paper report on the development and assembly of 3D components that can be used to construct a

variety of modular tensegrity structures. Included in this article is a more comprehensive overview of the research domain and a number of speculative design projects (Frumar et al. 2009).

Using 3D components in place of linear struts restricts the kinematics of each tensegrity module. When modules are interconnected, this property results in a more rigid and robust framework than conventional tensegrity assemblies. Moreover, 3D components significantly reduce strut congestion and fabrication complexity by minimizing the number of individual structural elements needed to induce a tensegrity state.

1.3 FORM FINDING – THE (INTER)ACTIVE DIGITAL MODEL

Once a series of tensegrity modules is interconnected, it is possible to generate a wide variety of forms by varying the length/pre-stress of tensile elements and the proportions of compressed components. While basic structures composed from a small number of modules are best explored as physical models, when an assembly reaches a certain size and level of complexity, it becomes impractical to build it physically during explorative phases of design. This "representational divide" becomes a significant limitation to the design process and suggests that a dynamic and ideally interactive digital model is necessary to support the early stage design development of sophisticated tensegrity structures. Calculating the shape of tensegrity structures in a digital environment requires form-finding procedures that can establish "a geometry compatible with a self-stress state" (Motro 2002), and generally speaking, this functionality is not supported within the current generation of CAE and CAAD software (Burkhart 2008; Sterk 2007).

In a publication just prior to his passing, the late Dr. Thomas Seebohm describes three-dimensional tensegrity structures generated from two-dimensional "topologies" using a Java applet named Struck (Seebohm 2008). Struck is a form-finding tool developed in 1998 by a computer programmer named Gerald De Jong, specifically to find the form of tensegrity systems (De Jong 1998). It activates otherwise inert geometry by introducing tensile and compressive forces. Struck calculates the form of a system given its initial geometry and the desired rest length of each "structural" element. The form-finding process is visualized in real time and uses color mapping to identify compressed components (red), tensile members (blue), and redundant structural elements (black). There is very little documentation about how Struck actually works, making Seebohm's research important for elucidating some of the mathematical principles behind the interface. From his descriptions, it is clear that Struck is based on relatively simple particle-spring logic and is sufficiently accurate to support the design exploration of complex tensegrity structures. One limitation noted by Seebohm is that the Struck interface does not conveniently allow complex topologies to be entered. To properly engage Struck as a design tool, it is necessary to develop a bidirectional link with standard CAAD software. The authors have had the privilege of access to Dr. Seebohm's digital archives containing his work on tensegrity structures, including an AutoLISP script he developed for generating Struck input data from two-dimensional line work in AutoCAD.

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 interdependent, global geometry can be manipulated by adjusting a limited number of local parameters. A recent publication by the authors (Frumar and Zhou 2009) presents detailed information about Struck, as well as an overview of alternate computational tools that can aid in the design of complex tensegrity structures.

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, the two components 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 300 mm was built using interlocking laser-cut timber and fishing line (fig. 1).

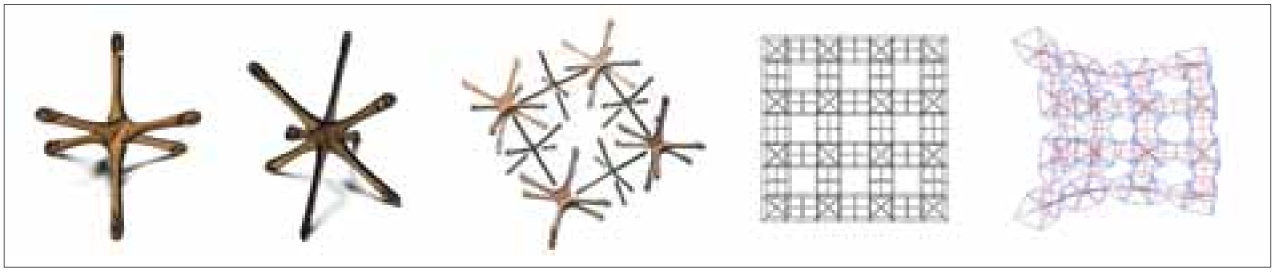

Figure 1 3D components, physical assembly, "inert" Rhinoceros geometry and "activated" assembly in Struck

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 “en masse.” The inert Rhino 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. Geometry exported from Rhinoceros, generally speaking, 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 if there are any elements that could be removed without compromising the overall integrity of the structure.

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 (fig. 4).

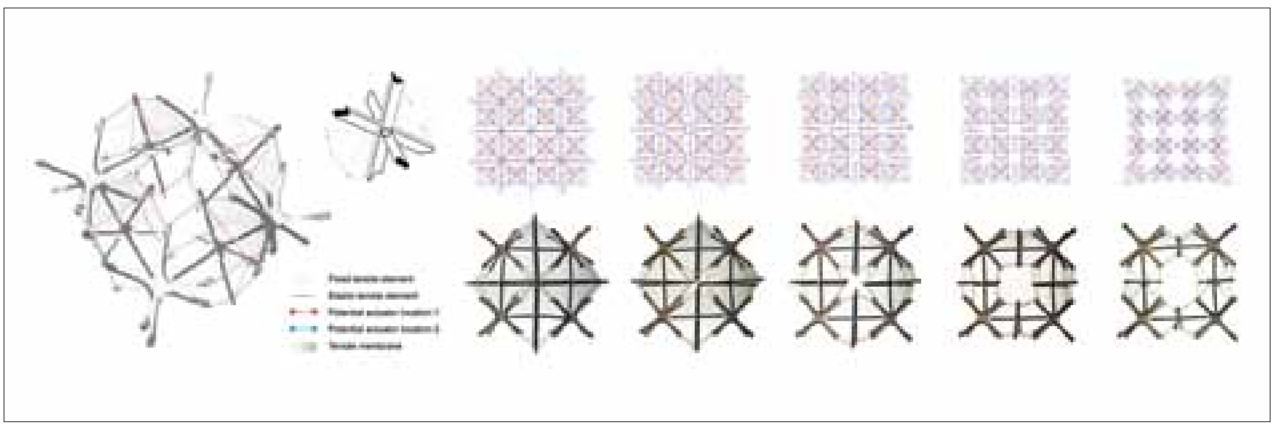

Figure 2 Gradient between closed and open states – digital and physical models

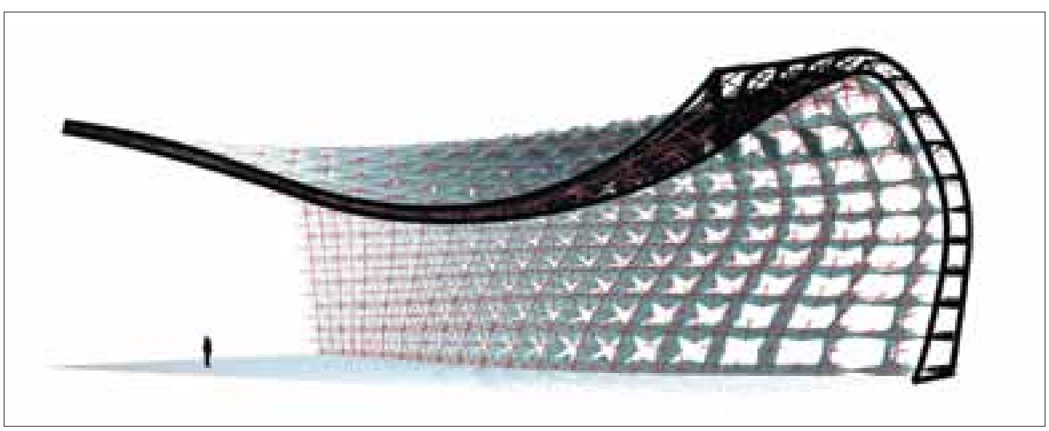

Figure 3 Visualization of responsive building envelope that can modulate heat and light by altering porosity and transparency

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 not necessary, as Struck was used to "tune" them carefully 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.

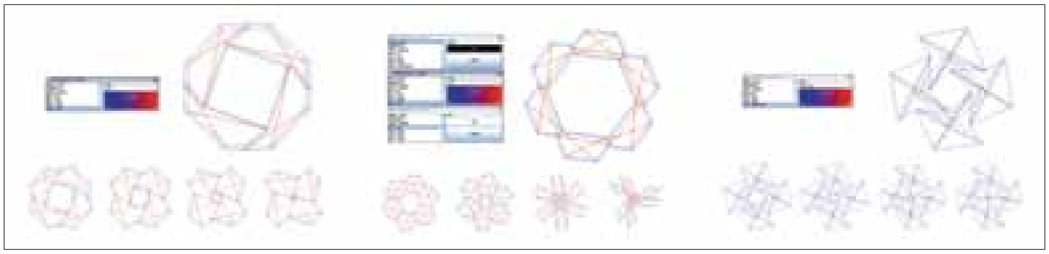

Figure 4 Alternate kinetic tensegrity grid configurations

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 was 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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