TENSEGRITY STRUCTURES WITH 3D COMPRESSED COMPONENTS: DEVELOPMENT, ASSEMBLY AND DESIGN

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ABSTRACT

Over the past six decades, the notion of tensegrity has prompted significant research in the fields of structural engineering and architecture. Tensegrity is of interest to architects and engineers wishing to explore lightweight and rapidly deployable structural solutions for non-standard architectural forms. Despite thorough investigation by a variety of researchers, the ability to determine, control, visualize and deploy tensegrity structures within building construction remains elusive. This paper presents a novel approach to tensegrity through the development and morphological analysis of 3D 'compressed' components. A range of physical models is presented to illustrate some of the configurations and arrangements that have been assembled by the authors.
Two speculative design projects implement a computational method of form finding that demonstrates a digital means of expanding the design potential of tensegrity structures. Although basic in its implementation, this form finding application is a significant step towards computational platforms where design and engineering information can converge. That is, digital modeling environments where form is inextricably linked with force and design conception is enmeshed with appropriate strategies for design realization.

Keywords: *Tensegrity, 3D Compressed Component, Form Finding*

1. INTRODUCTION

1.1 Tensegrity

The concept of tensegrity is relevant at many scales. It has been used to describe the configuration of the universe (Fuller 1975), the physiology of the human body (Levin 1982) and the structural behavior exhibited by carbon atoms, water molecules, proteins, viruses and other biological cells (Ingber 1997). Although initially conceived as a novel approach to structures for the purpose of art (Snelson 1990), research into tensegrity and its applications in architecture and engineering has a long history and many contributors. Richard Buckminster Fuller and Kenneth Snelson are regarded as the pioneers of 'tensegrity' – a contraction of the words tensile and integrity, coined by Fuller in his patent document. He described a tensegrity structure as "an assemblage of tension and compression components arranged in a discontinuous compression system." (Fuller 1962). Snelson submitted his own patent titled "Continuous tension, discontinuous compression structures" (Snelson 1965) and has referred to tensegrity as the "floating compression principle" (Snelson 1990). A more comprehensive definition and one that specifically covers the novel structures described in this paper is presented by Rene Motro:

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).

Tensegrity structures are mechanically stabilized through the interaction of discreet systems of discontinuous compression and continuous tension. By distributing structural forces through discreet paths, tensegrity networks eliminate the need for bulky elements and have a high strength to weight ratio, resulting in lightweight structures that are self-stressed and freestanding. An important property of tensegrity structures is that their shape depends not only on topological characteristics, but also on the elasticity and amount of pre-stress in the tension members. This results in re-configurable forms and deployable structures with variable rigidity "in which all parts exist in a dynamic equilibrium" (Hanaor 1992).

1.2 3D Compressed Components

Tensegrity is of interest in architecture and engineering fields as it enables the exploration of lightweight and rapidly deployable modular structures that have a high degree of geometric freedom and formal potency. However, despite thorough investigation by researchers, the ability to determine, control, visualize and deploy tensegrity structures within architectural construction remains elusive due to four primary reasons; strut congestion, fabrication complexity, inadequate design tools and poor load response (Burkhart 2008). It is important to note here that the majority of research and discourse to date has focused on class 1, 2 and 3 tensegrity systems constructed from tension cables and unidirectional compression struts. There are few practical examples where compression components consist of subassemblies that form more sophisticated geometries.

One such example is the classic X-Piece created by Snelson (Figure 1(b)), which is formed using planar X-shape elements and cables. A further example is Snelson and Fuller's original 'tensegrity mast', which uses 3D compressed components made from spokes radiating from the gravitational centre of a tetrahedron to its vertices. Some theoretical examples can be found in the work of B.B. Wang who has carried out extensive research into similar tensegrity structures, which he terms "non-contiguous cable-strut systems" (Wang and Li 2005). Importantly, Wang concludes that these assemblies display increased structural efficiency compared with conventional tensegrity systems (Wang 2004). The research presented here aims to elaborate on the design potential of tensegrity structures that utilize 3D compressed components.

Figure 1 illustrates the differences between a 1D bar, 2D X-shape and 3D tetrahedral tensegrity structure. Figure 1(a) is a simple 3 bar per level tensegrity, Figure 1(b) is the classic X-Piece created by Snelson in 1949 and Figure 1(c) depicts a tetrahedral member tensegrity tower created by the authors. It is clear that the 2D X-shape and 3D tetrahedral pieces are resisting compressive forces in these models. The different configurations offer each tower differing orientations and degrees of geometric and mechanical freedom. Using 3D compressed components restricts the internal kinetics of each structural module. The joints between each module govern shape variability and the joint configuration determines how loads are transferred and the degree of variability that can be achieved. Adjusting the length of cables between modules enables a wide variety of forms to be generated with a single tensegrity assembly.

According to the original principles and definitions outlined by Fuller, Snelson and others (Pugh 1976, Wang 1998, Motro 2002), a stable, self-stressed structure created by discontinuous

a. b. c.

Figure 1. *1D bar, 2D X-shape and 3D tetrahedral tensegrity 'masts'*

three-dimensional compressed components within a continuous tensile network also satisfies the definition of tensegrity. Importantly, using 3D components appears to alleviate strut congestion and fabrication complexity by minimizing the number of building elements needed to induce a state of self-stress.

2. 3D COMPONENT DEVELOPMENT

2.1 Geometric properties

Generally speaking, tensegrity structures are composed from an array of interconnected component-based modules. 3D components can be freeform, symmetrical or eccentric in shape. The design potential of 3D compressed component tensegrity structures depends on the geometry of the compression components, overall shape of the modules and in what manner the modules can be tessellated.

A 3D compressed component module suitable for use in architectural construction must satisfy the following requirements:

- Extreme vertices bound a volume
- 3D components connect to the tension network at extreme vertices
- 3D components are discontinuous
- Modules can tessellate in at least one direction

2.2 Constructing 3D components from 2D pieces

To investigate the feasibility of 3D compressed components, the authors began by exploring the tetrahedron, octahedron and icosahedron, as these three shapes are regularly proportioned and structurally stable platonic solids. Each shape became the basic framework for generating our compressed components. Principally, the components were developed by radiating spokes from the gravitational centers of each polyhedron to its respective vertices. The 3D components generated through this investigation were fabricated using both 3D printing and laser cutting. For practical and economic reasons, three basic 2D laser cut pieces were further developed to enable quick and easy assembly of the modules. We have named the 2D pieces X-Shape, Linear bar and Tetrahedral angle. These three pieces allow a variety of 3D modules to be rapidly assembled. Some of the modules are listed in Table 1 and illustrated in Figure 3.

3. PRACTICAL EXAMPLES OF MODULES AND STRUCTURES

For a tensegrity module to be useful in architecture it needs to be able to span and/or fill space. A module that can connect to other modules in a number of different directions will be of greater use to designers than one that can only extend in a single direction. A module that can tessellate in three dimensions and at a number of different scales thus enables a more refined level of design control.

Figure 2. *Laser cut parts for 3D components based on stable polyhedra: X-piece, Linear bar, and tetrahedral angle*

Modules	**Required pieces**
i. Tetrahedron	2 x tetrahedral angle
ii. Octahedron	Linear bar, X-piece
iii. Rectangular Prism	2 x X-piece
iv. Kite Prism	Linear bar, tetrahedral angle
v. Cubeoctahedron	2 x X-piece, 2 x tetrahedral angle

Table 1. *Assembly of 3D components*

i. ii. iii. iv. v.

Figure 3. *3D components assembled using 2D laser cut pieces*

Following are basic examples of initial design investigations constructed using laser cut timber pieces. The 3D components range in size from 50 to 250mm. These examples demonstrate the feasibility and design potential of tensegrity structures that utilize 3D compressed components.

3.1 Tetrahedron

The tetrahedral compression member is easily assembled for practical purposes using 2 tetrahedral angles connected perpendicular to each other and rotated 90 degrees. The resulting 3D compression member geometrically connects the tetrahedron's gravitational centre and its four vertices as shown in Figure 4.

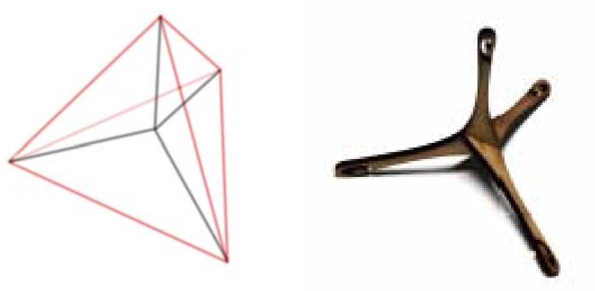

Figure 4. *Tetrahedron module and component*

We have explored this component in several examples. A seven level tensegrity tower was created as an initial investigation. The design of the tower is simple. Tension cables in both vertical and horizontal directions connect the tetrahedral modules, which are set axially one on top of the other. The horizontal cables are connected between the top vertices of each module and the bottom vertices of the module above. This specific vector driven relationship prevents the whole system from horizontal expansion. Vertical cables are then used to rigidify the structure. Thus a self-stressed system is created. As mentioned earlier and demonstrated in Figure 6, varying the length of tension cables makes it possible to generate a wide variety of forms with a limited number of module types. The vertical cables in the tower structure were manually adjusted to produce a slight curve in two directions. 3D compressed components extend the spectrum of potential tensegrity constructions. The tetrahelix tube shown in Figure 7 illustrates this potential. The tube is constructed with self-stressed tetrahedron modules (all four vertices connected by tension elements). Each module is connected with four other modules midway along their edge as shown. Although this tessellation pattern can be represented clearly in a planar diagram, in a physical model internal tensile forces must be countered by attaching one set of opposing edges to form a stable tube. In this arrangement tetrahedron modules form a counter-rotating set of spirals around a central axis. Due to the resulting spiral structure, any number of modules can be added to indefinitely enlarge the tube length and diameter. A similar structure can be formed using the kite prism, which demonstrates that 3D compression members can maintain their structural characteristics in certain arrangements even when critical angles are significantly varied. The ability to vary angles, proportions and lengths while maintaining structural characteristics makes 3D compression member tensegrity structures suited to associative modeling and digital fabrication.

3.2 Cuboctahedron

The basic 2D pieces developed for creating the tetrahedral and octahedral compression members were found to generate a range of unexpected elements. One example is the cuboctahedral compression member, which is assembled using two X-shapes and two tetrahedral angles. The resulting 3D component geometrically connects the cuboctahedron centre and its twelve vertices as shown in Figure 5.

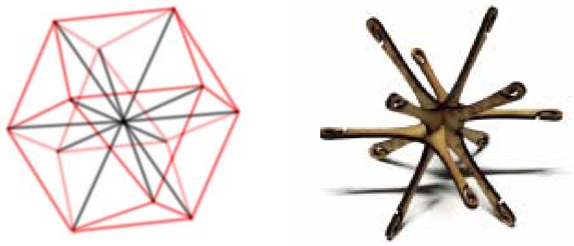

Figure 5. *Cuboctahedron module and component*

The cuboctahedron module proved itself useful as a node for a tensegrity frame system. A tensegrity node was developed that allows a structural frame to expand in six directions. The multi-axial node is formed using a cuboctahedron and four tetrahedron modules. It can be extended in the XY plane using tetrahedron modules and in the Z-axis using rectangular prism modules as shown in Figure 8.

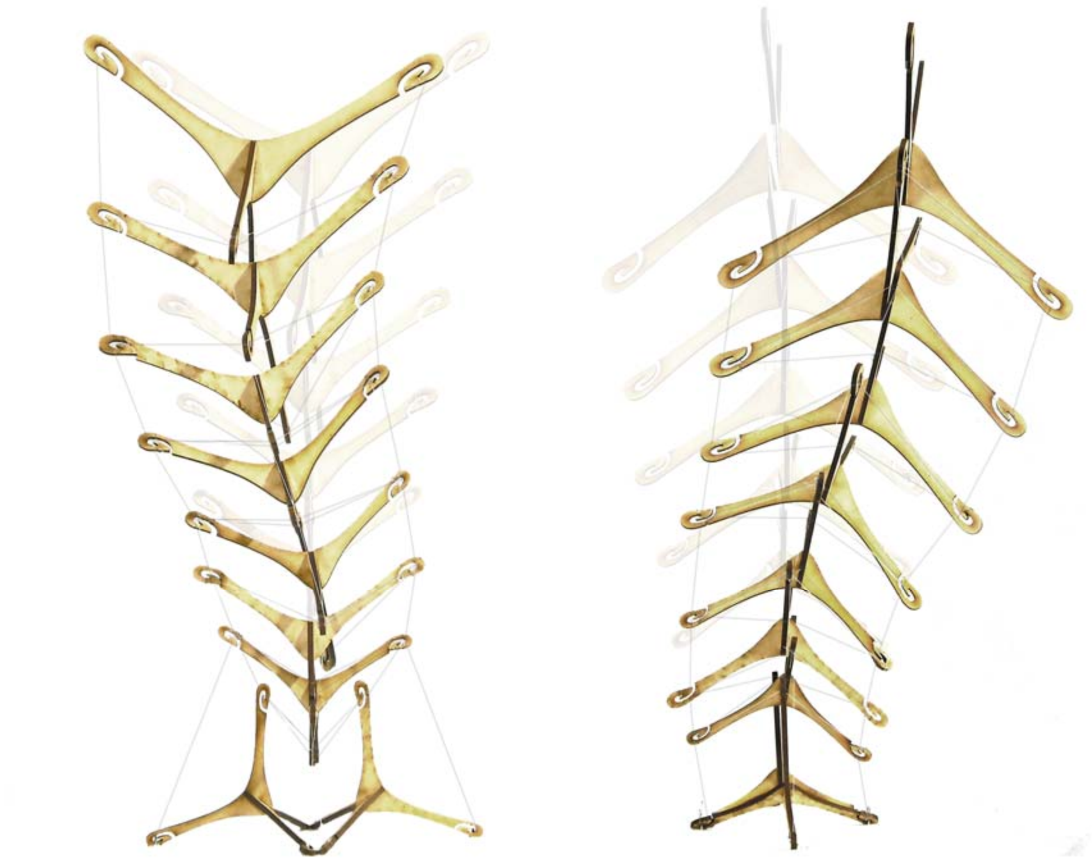

Figure 6. *Tetrahedral tensegrity tower*

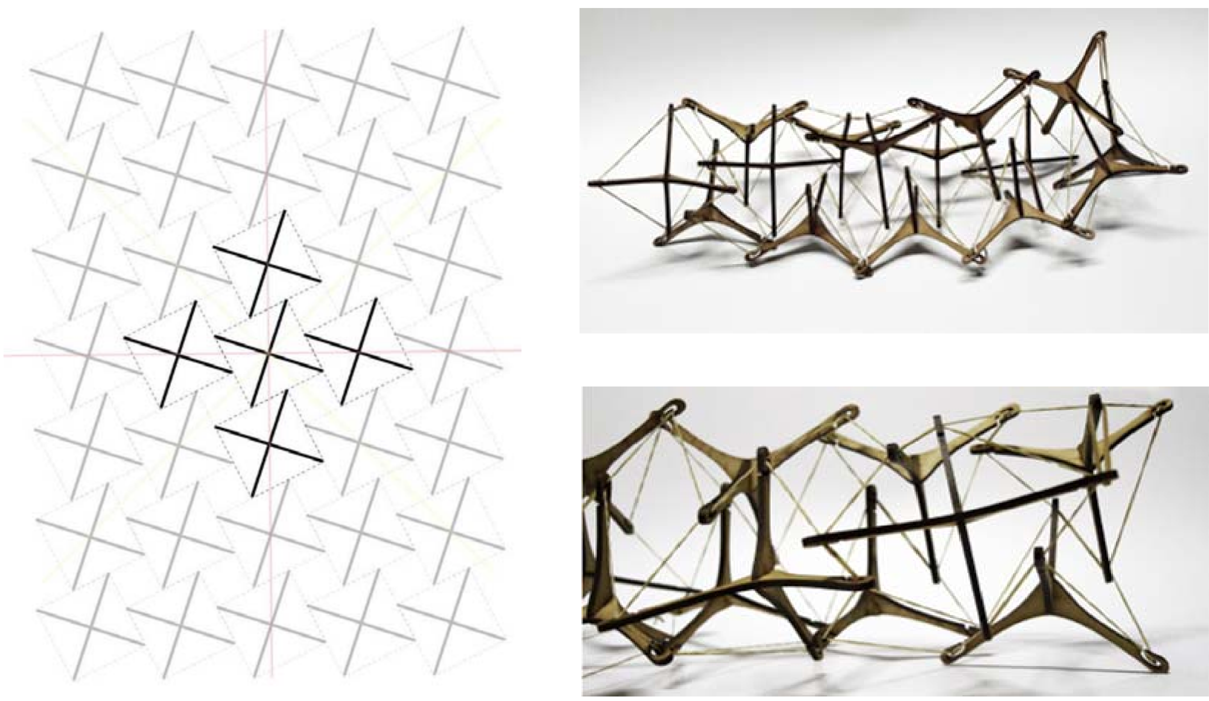

Figure 7. *Tessellating tetrahedron modules – tetrahelix tube*

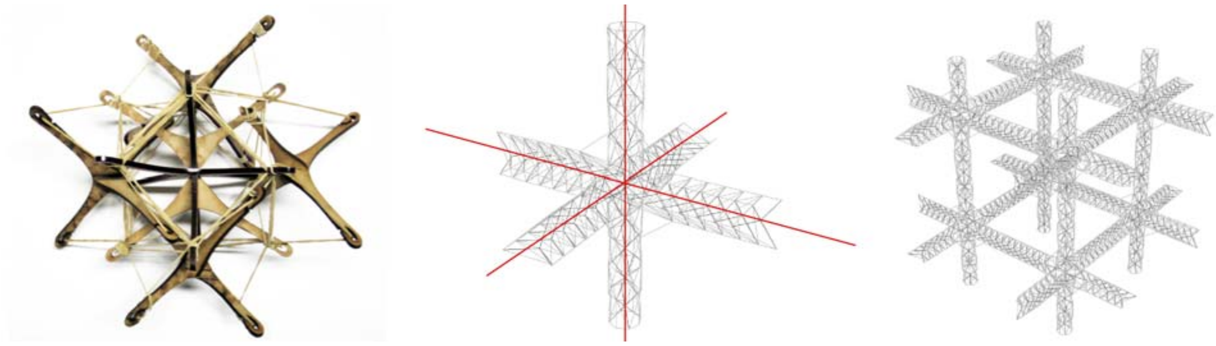

Figure 8. *Multi-axial node and frame system*

4. FURTHER MODULE DEVELOPMENT

The research carried out to date has shown that it is possible to reconfigure compressed component geometry so long as vertices roughly maintain the spatial relationships necessary to induce a state of tensional integrity. This characteristic enables design intervention within each module. Our team has approached this additional potential in a number of ways and we have subsequently developed a general procedure for designing tensegrity structures with 3D compressed components:

- Define a 3D component and tensegrity module suited to the project requirements
- Construct both physical and computational models of the whole structure to ensure stability and enable alternate forms to be quickly developed
- Build an analytic model to improve the strength to weight ratio and design of individual 3D components

This procedure allows designers to generate context specific modules suited to individual projects, explore the behavior and final shape of assemblies without building overly-complex physical models and engage strategies to further improve the characteristics of each module. Two projects that implement these processes are outlined below.

5. DESIGN EXAMPLES

5.1 A Tensegrity Footbridge

This project is a speculative design for a footbridge or similar structure. It is not sited and functions purely as proof of concept. A suitable 3D component is defined, and a number of physical models explore its design potential. A computational method of form finding is introduced to explore alternate forms for the bridge and to determine the shape of the final study model.

5.1.1 Defining a suitable 3D component

An example is shown in Figure 9 where the original tetrahedral compression member introduced earlier has been replaced by an inverted element that maintains the critical tetrahedral vertex arrangement. The laser cut component is designed as a cross-section suitable for bridge construction. It features a void in its centre that can be used to set the bridge deck.

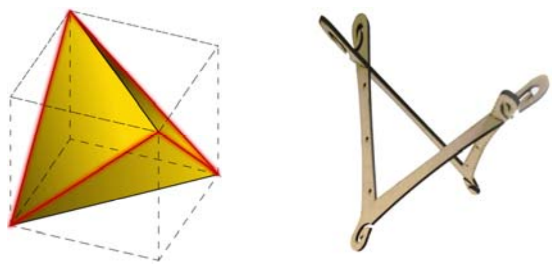

Figure 9. *Inverted tetrahedral component*

The new component enables axial tessellation similar to the tetrahedral tensegrity tower pictured in Figure 5. However, it should be noted this configuration introduces an alternate set of bending and torsion forces into the element that must be absorbed by rigid joints at each vertex of the final 3D component. These joints must resist large forces acting to collapse the element. Further assemblies were constructed to explore the effects of shifting the scale and proportions of compressed components and to test the notion of a membrane based tensile continuum. In all scale models the structure was observed to maintain self-stress. Some of these investigations are illustrated in figure 10.

Figure 10. *Shifting scale of compressed components and investigating a membrane based tensile continuum*

5.1.2 Using Computational Form Finding to Expand the Design Spectrum

We have discussed that once a series of tensegrity modules are interconnected, it is possible to generate a wide variety of forms by varying the length of tension cables and proportions of compressed components. While basic structures composed from a small number of modules are best explored as physical models, once an assembly reaches a certain size and level of complexity it becomes impractical to build 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. However, calculating the shape of tensegrity structures in a digital environment is no easy task and requires form-finding procedures that can establish "a geometry compatible with a self-stress state" (Motro 2002). Unfortunately, this functionality is generally not supported within the current generation of off-the-shelf CAE and CAAD software (Burkhart 2008, Sterk 2007).

In order to explore a variety of forms for the footbridge structure without painstakingly building numerous physical models, a unique Java applet named *Struck* was utilized. 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 provides color-mapping to identify compressed components (red), tensile members (blue) and redundant structural elements (black). Once a system converges to a stable state, it becomes possible to explore various shape transformations in real time by using a parameter slider to change the rest lengths of tensile and compressive elements (Figure 11). Because all structural elements are interdependent, global geometry can be manipulated by adjusting a limited number of 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 an upcoming publication by the authors (Frumar and Zhou 2009).

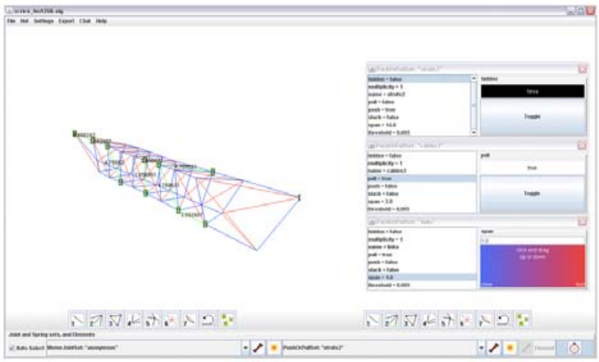

Figure 11. *Struck interface showing parameter panels*

5.1.3 Determining the Final Bridge Form

Struck is limited to dealing with linear compression struts and pin-joints. To simulate the behavior of the proposed footbridge it was necessary to develop a strategy that could prevent the 3D compressed components from collapsing. To achieve this, additional compression struts were added at the top and bottom chords of each component creating closed tetrahedrons. The additional struts simulate rigid joints by resisting the forces acting to collapse each compressed assembly. In Figure 11 and Figure 12 they have been hidden to clearly illustrate the intended structure.

Figure 12. *Alternate forms for footbridge developed in Struck*

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 arch. The edge cables are individually controlled with interactive sliders in Struck. Shortening the rest length of the cables along one or two edges distorts the structure from a rectilinear tube into a sharply arching form as shown in Figure12. This process is visualized in real time as mentioned earlier. The final form that we chose to develop further became a negotiation of the two extremes, offering a gentle slope suitable for a footbridge (Figure 13).

(Figure 15). The wire frame model generated in Struck was exported to Rhinoceros and fabrication information was extracted. The final 3D compressed components are an assembly of 2D laser cut timber pieces. Each component is interconnected and tensioned with fishing line. A comparison between the computational, digital and physical models in Figure 14 show them to be satisfactorily similar to conclude that Struck is a useful tool for finding the form of tensegrity structures with 3D compressed components. It is clear from the digital and physical models that the bridge conforms to the definition of tensegrity

Figure 13. *Design visualization of footbridge structure*

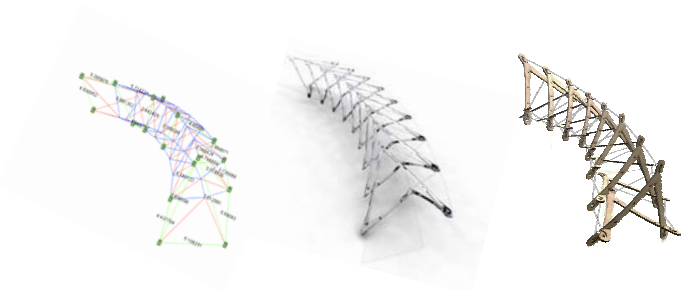

Figure 14. *Comparison of computational, digital and physical models*

5.1.4 Validating the Digital Model

Based on the computational model, a 1:20 scale model of the bridge was fabricated to verify the form finding approach and test the overall behavior and feasibility of the 3D components

structures introduced earlier as it is a stable, self-equilibrated system containing a discontinuous set of 3D compressed components inside a continuum of tensioned components.

Figure 15. *Tensegrity footbridge study – 1:20 scale model*

5.2 [near] Instant High-Rise

The concept for this project stems from the utopian notion of creating a high rise building structure that can be erected in a matter of days. In this design, two floor levels are suspended from the underside of each compressed component. This configuration results in a column free structural system. The 3D component used here is an evolved version of the inverted tetrahedral component introduce previously. The authors developed this proposal as an entry to the 2009 Evolo skyscraper competition based in New York. From 416 entries, [near] Instant High-Rise was awarded an honorable mention and has been singled out as exemplary in online architectural forums bringing “some new refreshing ideas [that justify] the persistence of this competition” (Boiteaoutils 2009). This response from the architecture community demonstrates the nascent potential of tensegrity structures with 3D compressed components in contemporary architectural design. Figure 16 illustrates two deployment strategies that were presented for the competition. These strategies were specifically developed for disaster struck areas. The image on the left is a tri-polar stand-alone configuration, while the image on the right depicts a more parasitic approach that makes use of remaining infrastructure.

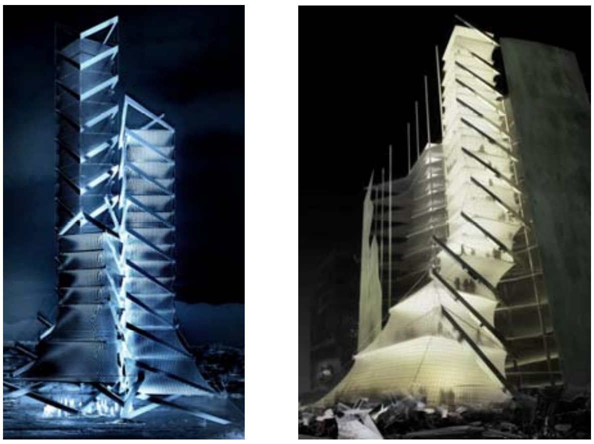

Figure 16. Alternate deployment strategies

5.2.1 Improving the Design of the 3D Component

A clear understanding of the forces exerted on compressed components makes it possible to build an analytic model that can be used to determine areas of low stress and thus opportunities to increase the strength to weight ratio of 3D components. The authors developed a numerical model of the tetrahedral component in Abaqus CAE. The structural analysis suggested that some material could be removed without compromising the integrity of the component. This process made it apparent that an entire edge of the frame could be removed provided the structural material could withstand the bending moments at the remaining vertices (Figure 17). Although unusual and perhaps not entirely practical or efficient from an engineering standpoint, such a component maintains the 4 tetrahedral vertices critical to its function as a compressed assembly. This novel component became the obvious architectural preference, as it enables the front façade of the high-rise building to remain free of compression elements.

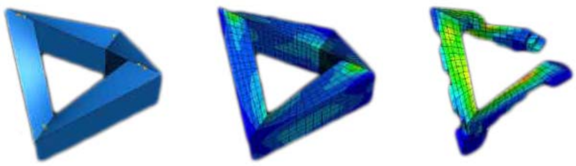

Figure 17. *Using an analytic model to improve the design of 3D compressed components*

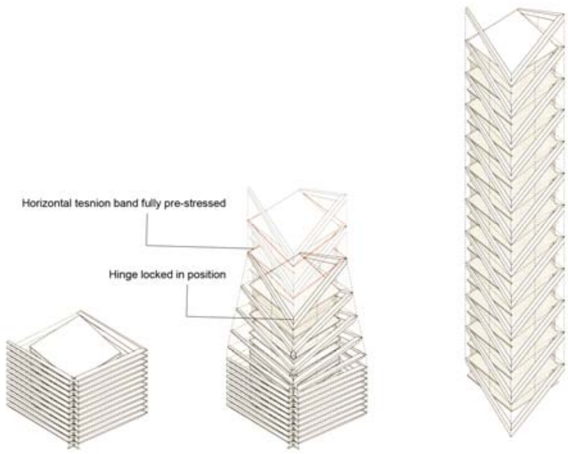

Figure 18. *High rise deployment diagram*

The component was further developed to enhance its functionality and suitability to the project goals. A hinge was added to enable the frame to be flat packed and thus transported easily. It is envisaged that all modules and cables would be pre-fabricated and connected offsite. The structure would be erected on-site by sequentially pre-stressing the horizontal tensile bands. When a horizontal band is fully pre-stressed, the connected components are structurally activated. The hinge enables the compressive assembly to pivot from planar into a V-shaped position and locks at a defined angle. This action self-stresses each tensegrity module respectively and elevates the preceding parts of the assembly, including the suspended floors. The procedure is shown in Figure 18.

5.2.2 Exploring Alternate High-Rise Forms

The design proposal illustrated above is essentially infrastructural and thus of decidedly regular geometry. Our investigations have demonstrated however that such a structural system can yield a wide variety of interesting architectural forms and spatial conditions. The commercial benefit of a rapidly deployed designer high-rise is obvious. Once the final high-rise strategy was proven to be functional, the Struck applet was used to explore the various shapes afforded by the structural system. Figure 19 shows some of the alternate forms that were explored. Note the size and proportions of 3D compression members are significantly varied in order to achieve the outcomes illustrated.

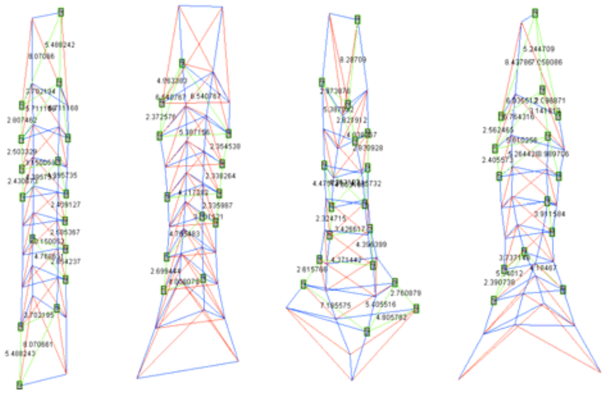

Figure 19. *Computational form finding to explore alternate high-rise form*

5. CONCLUSION

The work presented here is the result of a collaborative process between architects and engineers. It demonstrates a co-rational approach to designing tensegrity structures suitable for use in architecture. Mindful of preceding work in the field, a number of innovative solutions have been developed to tackle the significant difficulties encountered when utilizing traditional tensegrity structures in architectural constructions. Specifically, we have demonstrated that some of the difficulties associated with strut congestion and fabrication complexity can be overcome through the use of 3D compressed components.

This paper proposes a novel technique for constructing a variety of 3D components from 2D pieces. These components are shown to have the potential to generate a wide range of tessellation patterns. A number of digital and physical models have been produced to explore the new territory and several examples are presented.

Concurrently, a study into the design variables afforded by 3D compressed component tensegrity structures demonstrates that a series of stable forms can be generated from a single structural genotype. To capitalize on this potential within the design process, a form finding tool is utilized, which simulates the behavior of tensegrity assemblies in a computational environment. The Struck applet enables interactive manipulation of tensegrity structures and provides real-time visual feedback to verify if a structure is self-stressed and stable. Although basic in its implementation and level of accuracy, Struck is a significant step towards computational platforms where design and engineering information are synonymous; digital modeling environments where form is inextricably linked with force and design conception is enmeshed with appropriate strategies for design realization.

Tensegrity structures with 3D compressed components open up an expansive field of opportunities for designing lightweight, variable and modular frame systems. The research presented here is preliminary and serves to demonstrate their potential as a structural solution for non-standard architectural forms. The research presented here is expanded upon in two upcoming publications by the authors (Frumar and Zhou 2009). Specifically these publications deal with computational form finding and explorations into the use of 3D compressed components in kinetic tensegrity assemblies. It is important to note, further work is necessary in the fields of mathematics and engineering before these structures can be fully integrated into design and construction processes.

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