Struck calculates the stable, self-stressed form of a system given its initial geometry and the desired rest length of each spring. The form finding process is visualized in real time and provides colour-coordinated feedback to identify compressed components (red), tensile cables (blue) and redundant structural elements (black). Once a system converges towards stability, it becomes possible to interactively explore various shape transformations by using a parameter slider to alter the rest lengths of tensile and compressive elements (Figure C4d). Because all structural elements are force-dependent, global geometry can be manipulated by adjusting a limited number of parameters.

One limitation noted by Seebohm is that the Struck interface does not conveniently allow complex topologies to be constructed. To properly engage Struck as a design tool, a bidirectional link with standard CAAD software was required. Fortunately, I had the privilege of access to Dr. Seebohm’s digital archives containing his work on tensegrity structures. Among the files was an AutoLISP script he had developed for generating Struck input data from two-dimensional AutoCAD drawings. Building on Seebohm’s work, a script for Rhinoceros was developed to extend this process into three dimensions. To develop a Struck input file (.eig), initial geometry is developed in Rhinoceros using single line segments. The lines are translated into springs; the intersection of two or more endpoints becomes a node. Line segments are assigned either tensile or compressive properties using a layer naming convention. Multiple layers can be added to define variable rest lengths and properties for different elements.

Note 10. continued on following page.

10. At the 2008 ACADIA conference at Minnesota University in Minneapolis, I presented a paper titled An Energy-Centric Approach to Architecture. During the presentation I showed some early tensegrity studies. Afterwards, the session chair Philip Beesley asked if I would like some workfiles from the late Thomas Seebohm’s hard disk that were titled ‘Tensegrity’. Philip explained that he had been asked by Dr. Seebohm’s sisters to distribute the volumes of work to anyone who may find them useful. He warned that he had no idea what I might find. Upon my arrival back in Australia, I began to explore the folders. It did not take long to realise that I had unwittingly received a powerful yet simple piece of software that could be used to visualise the properties and behaviour of vast tensegrity arrays in real time.

Note 10. Initial script authored by Sam Rice (version 1.0). Updated by Tim Schork (version 1.1) to better structure element data.

Note 11. Initial script authored by Sam Rice (version 1.0). Updated by Tim Schork (version 1.1) to better structure element data.
Generally speaking, geometry exported from Rhinoceros is not initially active when opened in Struck due to the fact that the rest length of each spring equals its actual length. Activation is achieved by gradually adjusting the various lengths of members until all members are acting in tension or compression. As discussed, this process changes the colour of the geometry from black (meaning structural elements are carrying no load) to red (compressed components) and blue (tensile elements). Importantly, during this structural ‘tuning’ procedure it becomes immediately apparent if the assembly is stable or not, and also if there are any elements that could be removed without compromising the overall integrity of the structure.

The computationally lightweight particle-spring logic that underpins Struck enables real time simulation of large numbers of interacting entities. An Example from Seebohm’s archives illustrates a class 1 double-layer tensegrity grid with 3263 particles (Figure C4e). Furthermore, Struck provides a limited set of tools for editing the connective logic (topology) of particles and springs on the fly. This capability is a distinct and powerful advantage over conventional parametric and associative modelling environments where geometric dependencies must be declared from the outset and are not easily modified once established.

C5 Interim Summary

Addressing my desire to work in a more materially engaged manner, and with spatial systems that incorporate tensile elements as a means to reduce material consumption, led me to explore a particularly fascinating family of lightweight prestressed self-stable networks known as Tensegrity structures. These structures are of interest in architecture and engineering for their potential to support the rapid deployment of lightweight, geometrically complex and self-stable architectural forms.

10. Continued:

It was exceptionally gratifying to meet Philip and both of Dr. Seebohm’s sisters at the ACADIA conference the following year where I presented a paper titled Kinetic Tensegrity Grids with 3D compressed Components. The work I discussed was directly informed by and made possible through the tools and tips I found and unravelled within Dr. Seebohm’s tensegrity archives.
My preliminary research revealed a number of interesting potentials but also some significant limitations with their deployment at the scale of architecture. Investigating the complexities around controlling and fabricating conventional class 1 structures led to a collaboration with engineers from the Innovative Structures Group at RMIT University. Through an extensive process of applied research and development, we discovered a novel class of tensegrity structures that make use of 3D compression assemblies to restrict kinematics and reduce fabrication complexity, thereby facilitating more control during design and construction.

While this discovery is in itself a unique contribution to the engineering field \(^{12}\), in terms of addressing my initial intentions for this investigation, a suitable method of construction is only part of the requirement. To facilitate an integral computational design and manufacturing strategy, appropriate means of simulating the behaviour of tensegrity structures with 3D compressed components is also required.

The inadequacy of conventional design software to deal with force dependent geometry drove me to explore alternate modelling methods. This investigation culminated in the serendipitous ‘discovery’ of Struck - an interactive particle spring based applet capable of simulating the behaviour of tensegrity structures in real time. This capacity combined with the fabrication and construction logics developed earlier, provides the basis for an integral computational design approach in which material, structural and assembly logics are embedded as design parameters and serve to constrain early design exploration within a spectrum of rational and buildable structures and forms.

The next section describes a series of speculative and practice-based architectural studies that critically engage Struck as a tool for early design exploration. Through extensive prototyping these projects aim to validate this integral design to production methodology and test the extent to which such an approach might facilitate deeper insight into the material behaviour and potentials of tensegrity structures.

\(^{12}\) Evidenced by publication in the Journal of the International Association for Shell and Spatial Sturcutres (JIASS) in 2009. See Appendix for full paper.
C6 DESIGN STUDIES

C6-1 Flexible Footbridge
C6-2 [near] Instant Highrise
C6-3 Kinetic Tensegrity Grid Structures
C6-4 Ouroboros
C6-5 New City Vision
C6-6 Tensegrity Barrier
Description

This study is a speculative design for a footbridge or similar structure. It is not designed for a specific site and set of constraints. Instead, it functions purely to test the feasibility of using Struck as a tool for early design exploration. Since Struck is limited to dealing with linear compression struts and pin-joints, a particular aim of this project is to develop a strategy for simulating tensegrity structures with 3D compressed components that have rigid joints and can be complex in shape.
Defining a suitable 3D component

To explore these ideas, a simple 3D compression member was desired, which 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 minimize complexity a four-sided compression element was developed based on the structurally stable tetrahedron. An example is shown in Figure C6-1a 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.

The new component enables axial tessellation similar to the tetrahedral tensegrity tower pictured in Figure C3g. It should be noted this configuration introduces an alternate set of bending and torsion forces into the compressed assembly 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 C6-1b.
Determining the Final Bridge Form

Once satisfied that the 3D component would be suitable for a bridge design, an initial 3D model was created in Rhinoceros. To faithfully simulate the behaviour of the proposed footbridge structure in Struck, it was necessary to develop a strategy that could prevent the pin-jointed compressed components from collapsing. To achieve this, additional compression struts were added at the top and bottom chords of each component, creating closed tetrahedron modules. The additional struts simulate rigid joints at the vertices by resisting the forces acting to collapse each compressed assembly. In Figure C6-1b and Figure C6-1c they have been hidden to clearly illustrate the intended structure.

Early physical models had revealed 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 Figure C6-1c. This process is visualized in real time as mentioned earlier. The final bridge form was a negotiation between the two extremes that offers a gentle slope suitable for a footbridge.
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 behaviour and feasibility of the 3D components (Figure C6-1d,e). The wire frame model generated in Struck was exported to Rhinoceros and fabrication information was developed. 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 C6-1d show them to be satisfactorily similar to conclude that Struck is a useful tool for exploring alternate forms of tensegrity structures during conceptual design phase. It is clear from digital and physical models that the bridge conforms to the definition of tensegrity 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 C8-1a
Tensegrity footbridge study
1:20 scale model; MDF, fishing line
Description

Traditionally, high-rise buildings are predicated by maximum economic return and are thus associated with commercial endeavor and opulence. At the most pragmatic end of the market high-rise buildings tend to be conventional, formulaic architecture that does not involve risk taking in either design or construction. This project recasts the initial ambition for vertical expansion. It envisages a rapidly deployable structure that will provide centrally located resources in areas struck by disaster. The tensegrity principle is explored for its potential to provide a feasible structural system that enables the deployment of a [near] instant skyscraper.

This design proposal was developed in collaboration with Farzin Lotfi-Jam (Cache Studio) as an entry to the 2009 Evolo Architecture Magazine skyscraper competition. The motivation for this project was based on earlier observations regarding the incredible flexibility and adaptive nature of tensegrity structures. In particular, the tensegrity concept was noted as being a good candidate for developing rapidly deployable architectural structures. From 416 entries, [near] Instant High-Rise was awarded an honorable mention and has been singled out as exemplary in online architectural forums by bringing “some new refreshing ideas [that justify] the persistence of this competition” [Boiteaoutils 2009]. A Swiss civil engineer who maintains a blog dedicated to tensegrity structures has also commented that [near] Instant High-Rise “is an excellent tensegrity project. The project highlights not only architectural aspects but also exploits the structural properties of tensegrity structures for adaptive architecture” [Tensegrity Structures 2010].
This response from architecture and engineering communities demonstrates the nascent potential of tensegrity structures with 3D compressed components in contemporary design. The title page and Figure C6-2a illustrate two deployment strategies that were presented for the competition. The image on the title is a tri-polar stand-alone configuration, while the image on the right depicts a more parasitic approach that makes use of remaining infrastructure. The full competition entry can be found in the appendix.

Improving the 3D Component

The 3D component used in this design proposal is an evolved version of the inverted tetrahedral component introduced previously. For the purposes of this proposition, the issue of transportation to disaster zones means that decreasing the overall building weight is critical. Gaining a clear understanding of the forces exerted on compressed components through physical model making during the previous project made it possible to develop an analytic model of the tetrahedral component in Abaqus CAE. BESO was then used to remove redundant structural material. The results from the BESO process suggested that an entire edge of the compression assembly could be removed without compromising compositional or structural integrity. Altering the composition in this manner introduces significant bending and torsion within compressed assemblies that must be absorbed by exceptionally robust rigid joints at each vertex of the final 3D component (Figure C6-2b). Although unusual, such a component maintains the 4 tetrahedral vertices critical to its function as a compressed assembly. This novel configuration became the obvious preference, as it not only reduces material consumption but also enables the front façade of the high-rise building to remain free of visually intrusive structural elements.
Deployment

The compressed component assembly was subsequently refined to enhance its functionality and suitability to the project goals. A hinge was added to enable flat packing. It is envisaged that all modules would be pre-fabricated and connected offsite. The structure would be erected on-site by sequentially pre-stressing the horizontal tensile bands. Once a horizontal band is fully pre-stressed, the compression assemblies are structurally activated. The hinge enables each level to pivot from planar into a V position. This action self-stresses each tensegrity module respectively and elevates the preceding parts of the structure, including two floor levels suspended from the underside of every compression assembly. The coupling of the tensegrity exoskeleton with the suspended floors acts to increase the overall stiffness of the structure and enables column free floor space.

Exploring Alternate High-Rise Forms

The [near] Instant High-Rise project is essentially infrastructural and thus of decidedly regular geometry. However, the commercial benefit of a rapidly deployed designer high-rise is obvious. To this end the Struck applet was used to explore the various shapes afforded by the tensegrity system devised.

Figure C6-2e shows some of the alternate forms that were explored. In contrast to the competition entry, the size and proportions of 3D compressed components are significantly varied in order to achieve a wide variety of interesting architectural forms and spatial conditions.
Description

Two of the 3D components developed earlier were noted for their ability to interconnect. When attached in a particular manner, these two components form a rigid tensegrity grid with regular cubic openings. The grid is infinitely extensible in three axes. As previously demonstrated, adjusting the length/prestress of tension elements makes it possible to construct a wide variety of complex space filling geometries.

Initially, the aim of this investigation was to explore the architectural potential of this particular grid assembly using Struck. The tensegrity grid was expected to facilitate the construction of a doubly curved building envelope using only two unique compressed components (Figure C6-3a). To verify that such an assembly would be self-stressed and structurally stable, a physical model approximately 300 x 300mm was built using interlocking laser cut timber and fishing line (Figure C6-3b).

Once the stability of the tensegrity grid assembly was verified through physical model-making, a digital model was created in Rhinoceros. The inert Rhino geometry was used to generate the input data for an active digital model in Struck.

Figure C6-3a Two unique 3D components

Figure C6-3b 3D components, physical assembly, and ‘activated’ assembly in Struck
Activating the Grid in Struck

It was initially envisaged that Struck would provide a means of linking architectural form generation and visualisation to previously established material, structural and assembly logics. Since Struck is limited to dealing with linear elements, it was necessary to devise an appropriate approach to simulating the behaviour of the chosen 3D components. The final strategy used a series of linear struts that intersect around a central point but do not connect to each other. Their intersection in Struck arises through a balance of forces rather than because of a geometric constraint or additional stabilising elements.

Within the initial Rhino model, two tension ‘spines’ were placed on different layers so that they could be controlled independently in Struck. To achieve double curvature, a vertical spine was added to one side of the structure and a horizontal spine was added to the other. By adjusting the rest lengths of these virtual ‘muscles’ in the active Struck model, it becomes possible to manipulate the shape of the overall assembly from flat to doubly curved and back. The initial geometry and activated assembly are illustrated in Figure C6-3c.
Unexpected Potential

Activating the inert Rhinoceros geometry in Struck proved particularly rewarding. It became apparent during initial phases of the ‘tuning’ process that the grid assembly could be distorted in a number of unintended ways. In particular, the interactive nature of the Struck visualisation unexpectedly revealed how this configuration could be used to potentially construct a self-supporting building envelope that responds to environmental changes by actively or passively altering shape, porosity and/or transparency. The active digital model revealed an appropriate means of controlling this movement through a series of additional cables located in the positions shown in Figure C6-3d. The new cables enable transformation of the entire structure from a closed to open state. It became apparent that a rotating joint mechanism in the required position would allow the porosity/ transparency of the assembly to be modified both locally and globally without compromising structural integrity. The Struck model also revealed that shape and porosity controllers are independent and can thus be operated individually or in unison.

A physical model was built to test the discoveries made in Struck. The model was constructed with rotating joints in the required locations. Figure C6-3e demonstrates that the physical model operates analogously to its digital counterpart and maintains stability in all positions. This exercise made it clear that active [computationally driven] or passive [eg. heat-activated] actuators could potentially be used to control the porosity of the assembly in a full-scale construction.
Exploring the Adaptive Kinetic System

An expanded digital model was developed to further explore the architectural potential of the [now kinetic] tensegrity grid structure. A large swathe of the structure was generated in Rhinoceros (Figure C6-3f). Once again tension ‘spines’ were introduced to govern global form and specifically placed actuators control porosity. Activating this tensegrity configuration in Struck demonstrated that such assemblies might be applicable to responsive, freestanding shell-like structures or self-supporting building envelopes (Figure C6-3g).

Although this study requires a significant amount of further work before it could be confirmed as an effective approach to generating responsive building structures and systems, the physical models that were produced and the accompanying images serve to illustrate the fundamental [and yet under-explored] feasibility of deploying kinetic tensegrity grids in architecture to modulate environmental qualities.
Further Grid Assemblies

The process of activating the initial grid revealed how force-based representation can be of significant benefit to designers. Struck provides a level of abstraction that is surprisingly useful. While nodes are continuously re-negotiating their positions based on the rest lengths of the elements connecting them, the elements themselves can pass through each other. This capability makes it possible to visualise structural behaviours that would otherwise be impossible. In this way, new and unexpected kinds of structural assemblies, mechanisms, connection details and behaviours can be explored and devised.

Examples of self-supporting kinetic tensegrity grids requiring novel 3D compressed assemblies are illustrated in Figure C6-3h. Each of the grids is infinitely extensible in at least two axes and has its own structural character, mode of actuation and aesthetic impact when deployed on a large scale. A common feature is that shape, porosity and transparency can be controlled with correctly placed actuators and suitable compressed component mechanisms.

The inactive geometry for these ‘experimental’ assemblies was generated in Rhinoceros based on a heuristic trial and error process. Instead of building physical models, Struck was used to ensure the stability of these assemblies and explore their potential for actuation. This investigation aimed to further explore the notion of using interactive force-based representations (such as Struck) to explore potential structural mechanisms that could be suited to adaptive/responsive architectural design.
Description

Ouroboros is an interactive sculpture devised in collaboration with Melbourne-based visual, multimedia and performance artist Victor Holder. It was first constructed outdoors as an installation for a music festival in March 2009. Ouroboros has since been reconstructed at numerous indoor exhibitions. This project came about through an informal discussion with the artist. At the time, I was interested in constructing a full-scale tensegrity structure and Victor was interested in pursuing interactive public art that incorporated performance and multimedia to represent change and transformation. After deliberating over some physical tensegrity models, we both noted that the flexible and dynamic nature of basic Class 1 structures provided an interesting opportunity for collaboration (Figure C6-4a).

Figure C6-4a
Hexagonal Class 1 tensegrity structure constructed from plastic tubes and elastic

Initial concept sketch by a
Design

After a period of design development, the Ouroboros concept was conceived as a dynamic three-dimensional projection screen. It was envisaged that people would be able to climb on the structure and thus manipulate it into different geometries by applying force. As part of the installation, a number of choreographed performances were to take place that would make full use of the flexibility, dynamism and load bearing capacity of the final projection screen. Figure C6-4b shows an initial concept sketch by the artist.

The basic concept was to deploy a three to four metre tall Class 1 hexagonal tensegrity prism in which compression elements would be connected with a strong elastic material such as bungy cord. Lycra stretched between each ‘bay’ of the prism would provide an elastic surface to project imagery onto (Figure C5-4c). All elements of the structure would be elastically connected and free to move, creating a dynamic yet stable structural framework.
Construction

To test the design concept, a 1:5 scale model was produced using steel tubes, rubber [bicycle tyre inner tube] and lycra (Figure C6-4f). Once it was established that this structural configuration was suited to our purposes, we set out to find materials that could be used to construct the full size version. My own intimacy with the structural system made it easier to judge the kinds of materials needed and design simple yet robust connection details.

The final installation is composed of:
- Six 100mm diameter PVC tubes (3.5m).
- Twelve bolts
- Eighteen spring hooks
- Twenty Four recycled rubber fan belts
- Five metres of rope
- Fifteen m2 white lycra

An appropriate construction sequence was devised based on experience from making scale models. The construction sequence for the full scale structure is as follows:

Each PVC tube is connected to a mildly prestressed rubber cable at the top and bottom via bolts and spring hooks. One quarter of the way down, a third spring hook is attached to the rubber. The process of construction requires the third ‘floating’ spring hook on each cable to connect to the bolt located at the top of a neighbouring tube. This connection is most easily achieved by beginning with one tube and sequential adding neighbouring tubes at an angle of approximately 120 degrees [for a hexagonal prism]. This aggregation process results in the configuration shown in Figure C6-4e.
The free ends of each tube are then connected via rope. The structure is erected by gradually tightening the rope while lifting the central ring. Although the process of construction had been roughly predefined using scale models, the length and prestress of the rubber cables required significant fine tuning to achieve just the right balance of form and flexibility (Figure C6-4g).

Ouroboros was designed and fabricated to be easily transportable and deployable. The final installation was constructed and tested in a studio prior to being dismantled and reassembled on site. Although this structure has been deployed numerous times since, it has not been necessary to dismantle the main structural frame as we have found that it can be easily compressed and held in a tubular fashion using rope. To deploy the structure simply requires untying the rope and manoeuvring the PVC tubes into their equilibrium positions. As yet the rubber fan belts that govern flexibility and structural integrity have shown little sign of fatigue or elongation.

Opposite Page:
Figure C6-4g
Prestress trial one and two
Description

New City Vision is an unbuilt proposal for a 32.65 metre tall signage tower located on a prominent site in Melbourne, Australia (Figure C6-5a). The tower was to stand on the perimeter of the CBD, within a site that has been long dormant. It was to signal the forthcoming construction of a new city precinct and invite the public to explore this exciting development through a web-based portal. Unfortunately, this ‘live’ project was discontinued after the first round of documentation for reasons outside of the design team’s control.

The tower concept was initially conceived by a marketing company together with the site developer. According to the original brief, the tower was to look unsteady, like it’s under construction. Coupled with this aesthetic, the developer wanted to use scaffolding as the primary construction material. The Innovative Structures Group (ISG) with whom I had been collaborating was invited to explore ways of realising the design concept in an interesting and novel way.
Initial Design

The initial ‘artists impression’ was prepared by the marketing company and is pictured in Figure C6-5b. The developer expressed the desire for something more striking and unusual. The context of the project seemed to suggest that a tensegrity configuration might be suitable as tensegrity structures appear to contradict the laws of ‘classical’ physics by containing ‘floating’ compression assemblies. After an initial discussion, the clients agreed this would be a fitting departure point for the design process.

To comply with the brief in an elegant and exciting way our team initially proposed a structure based on the compressed assembly used in the footbridge study (Figure C6-5c). The V-shaped modules were to be constructed from four scaffolding tubes connected to each other via swivel couplers and welded. Each compression ring would be connected to others via a series of pre-stressed steel cables as shown in Figure C6-5d. The proposed form would be constructed by varying the length of the vertical tension elements between each module.

Design Development

Feedback regarding the initial proposal was that it appeared too finished – more like a sculpture than a work in progress. Along with this design, numerous examples of alternate tensegrity based constructions were presented. The clients were particularly taken by the aesthetic achievable with traditional class 1 and 2 tensegrity structures. One of the issues flagged within this meeting was that despite being made from scaffolding whose erection typically does not require a construction permit, the tower was fairly large and had to support a series of 1.5 metre lettering at its peak, thus an engineer would be needed to perform a structural analysis and to verify its stability under gravity and wind loads. As noted earlier, structural analysis presents a significant problem in the case of tensegrity structures due to the fact that typical CAE software cannot adequately describe their structural behaviour or properties.

To overcome this issue, the second design iteration began to look at the potential of using class 2 structures in which compression elements are discontinuous vertical spirals. The number of spirals can range from three to infinity and a wide variety of stable cylindrical forms can be constructed by altering the proportions of the structural elements. From physical modelling and precedent studies 16, our team understood that coupling a series of continuous and rigid spiral ‘columns’ via pre-stressed tension elements should overcome the structural indeterminism of the system and theoretically enable analysis with conventional CAE software. In other words, we reasoned that if the joints between struts are considered fixed, and first level struts are anchored to the ground, then the whole assembly should be statically determinate.

16. A good precedent for this class of tensegrity tower can be found in Rostock Germany. A number of papers and articles have been written discussing its design, engineering and construction. It is constructed using six stacked tensegrity modules and stands 62.3m tall from its base to the needle point.
A rough wire and string model was produced as proof of concept. During preliminary discussion with a structural engineer, doubt was expressed about using scaffolding to create the tower, however he agreed that the simple wire model we presented appeared relatively stiff and offered a possible structural solution for the tower. During this meeting, which involved all key project stakeholders, it was agreed that a pentagonal class 2 tensegrity structure would be sufficient to create the kind of ‘unsteady’ aesthetic that was desired (Figure C6-5e). Despite the unlikelihood of using scaffolding as originally envisaged, the developer expressed that they were still keen to continue the design process along this trajectory.

**Final Design**

An active virtual model was created in Struck to explore a variety of potential forms for the tower. Anchor points were added to the model to simulate planar footing. These can be seen in Figure C6-5f as black points at the base of the structure. The shape and height of the final structure was developed by altering the various lengths of tension and compression elements. This procedure served to generate a structurally stable form that would ensure visual prominence of the signage on the city skyline (Figure C6-5g). As with all tensegrity structures, increasing the amount of tension in the system increases overall stiffness, thus our team reasoned that a fairly robust tower would be achievable provided enough pretension could be induced within the final structure.

A 1:20 scale model of the proposition was constructed using wooden dowel, flexible rubber joints and string. Though slightly different than the intended design due to its hand crafted nature, this process validated the stability of the structural configuration and provided a platform for further discussion with the engineer and key stakeholders.
Figure C6-5g
Final Proposition: 1:20 scale model and proposed signage detailing

Signage Mounted on Linear Brackets Situated Between Two Compression Spirals. Each Word is Slightly Rotated in Space due to the Angle of the Spiral Structure

Tension Member

Possible Construction Details for Rigid Spiral Joints:
1. Scaffold Compression Members Connected by Swivel Couplers and Welded into Position
2. Bent Tubes
Structural Indeterminism

The tower design we proposed relies on pretension for its integrity and stability. In theory, a prestressed configuration of this nature should result in a structure with a high strength to weight ratio. The tower proposition was envisaged to consist of relatively narrow and lightweight ‘compression spirals’ coupled via a pre-stressed cable network. The greater the pretension, the more stiff the tower. Increasing pretension in turn amplifies the forces within compression elements. The final tower must therefore be a perfect balance of tensile and compressive forces.

Once all parties were satisfied with the intended design, a 3D model based on the active Struck model was issued to the engineer for preliminary appraisal. The feedback from the first round of structural analysis effectively marked the beginning of the end for the project. According to the engineer, the computational analysis would not converge. In other words, a full set of meaningful data could not be obtained as the computer was reporting that the structure was unstable. The data that was obtained suggested that deflections due to self-weight would be unacceptably large (Figure C6-5h). Despite attempts to address this issue through our choice of structural configuration, this feedback was not entirely unexpected as our team was already aware that the non-conventional and somewhat counterintuitive structural configuration of tensegrity structures poses a significant challenge to conventional modes of structural analysis.

The reason behind this complication is that a joint or ‘node’ within a tensegrity structure can be considered stable as long as it is spatially defined in three dimensions, i.e. fixed in space by at least three tension elements. In structural terms however, such an arrangement is considered to be statically indeterminate as there are more unknown forces at a given node than equilibrium equations available to solve for them (Estrada 2007).

Design and engineering teams met in an attempt to resolve the issue. A sequence of alternate analytic approaches were cycled through to determine the source of the problem. A significant complication was that the design team was familiar with the behaviour of tensegrity structures but not the various methods of analysis used by engineers. Concurrently, the engineering team was familiar with tools of analysis but not the behaviour and characteristics of tensegrity structures. At the conclusion of this period of experimentation it became apparent that accurately determining the structural behaviour of our tower and the forces within its elements under various load conditions was not a trivial task with the tools at hand.

Figure C6-5h
i. Deflections of original structure due to self weight
ii. Deflections of non tensegrity structure due to self weight
iii. Deflections of final structure with guywires

17 The analysis software used was GSA Analysis by Oasys. The extended GSA Suite is capable of form finding tensegrity structures. A preliminary example that integrates parametric modeling with GSA can be found at http://geometrygym.blogspot.com/, accessed 24.02.11
The design team tried to explain that the obtuse analytic results were most likely a limitation of the software or the particular mode of analysis being utilized. However, despite access to the scale model and precedent studies describing a comparable tower constructed at Rostock, Germany in 2003 [Klimke & Stephan 2004, Schlaich 2004, Carstens & Kuhl 2008], the engineering team maintained that it was due to the physical instability of the structure. What was particularly interesting was that the engineers attempted to solve the problem of instability by increasing the size, and thus both the strength and weight of the compression members without much thought regarding the cable network. In their minds, the two systems were not interdependent and the tension network was certainly not the primary structure of the system.

Due to the growing sense of risk and time constraints, the only feasible resolution to the problem appeared to be redesigning the structure. The engineers proposed a structural solution that presented itself as tensegrity but was actually stabilized in a more conventional way using moment resisting truss connections and elements. The updated configuration was found to be statically determinate, however engineers were not satisfied with the amount of deflection at the tower tip (Figure C6-5h). To reduce this value, the engineers specified a series of guy wires that would hold the tip in place (Figure C6-5i). Although this solution offered one way of overcoming the problems encountered, from a design perspective it significantly compromised the original intentions of the design team and the client.

This proposition was nonetheless documented for construction and sent to a fabricator for a preliminary quote (Figure C6-5i). The design team was not privy to the outcomes from this stage of the process. The tower has not been erected, thus it is assumed that the quote for construction did not meet the budget constraints.
**Description**

The Greater city of Dandenong just outside of Melbourne, Australia is currently undergoing extensive urban renewal. As part of this upgrade, a new public plaza and shared pedestrian / vehicle zone will link Dandenong railway station with the nearby city centre. This project is being undertaken in a number of stages. To provide a visual and physical barrier between completed stages and yet to be developed areas of the site, the landscape architects engaged on the project proposed that the cyclone fencing typically deployed in such a scenario be replaced with a visually appealing dividing wall that adds to rather than detracts from the new streetscape.

Dr. Charles Anderson, one of the directors of Stutterheim / Anderson Landscape Architecture, was familiar with tensegrity structures in general and my research in particular. He had previously determined that such a system could provide a compelling design solution. I was engaged to help develop a detailed design proposition for this infrastructural element. The basic brief that we were working from required a 20m barrier that was at least 3m high. There was a possibility that this structure may need to be shortened, extended or moved as the upgrade proceeded. Further to this the amount of site preparation needed for deployment had to be taken into account and limited.
Design

The design phase progressed quickly due to time-constraints. While there was a significant amount of early experimentation, the tensegrity configuration explored in the kinetic grid study emerged as the most appropriate formation. The reasoning behind this decision was that this particular arrangement is easily constructed, modular, self-stable and re-configurable.

The design proposal was put forward to a committee consisting of urban planners, council representatives, project managers and a member from VicUrban. A Struck model illustrating the geometric potential of the structural configuration (Figure C6-6a) and a 1:10 scale physical model demonstrating stability and constructability were presented (Figure C6-6b). Despite flagging the potential issues surrounding structural analysis, the committee unanimously agreed that the design should be pursued.

Costing

The tight schedule forced a premature discussion with regards to construction. The 1:10 scale model was considered by fabricators to represent not just the stability of the system but also the construction logic of the 3D components. The 3D components in the physical model were made from intersecting 6mm lasercut ply. The fabricator assumed that the full-scale components would adhere to the same logic of assembly.
Obviously, scaling up the construction logic of the scale model resulted in complications. To minimise the weight of the structure, the fabricator considered each component to be made from intersecting pieces of lasercut 3mm steel sheet. With this configuration however, the extremities of the final 1.2 m$^3$ components would be too flimsy to resist the immense forces in the system. To overcome this issue, the fabricator proposed to weld a stabilising flange around the entire periphery of each 3D component (Figure C6-6c).

The final quote for construction came in at AU$70,000 for the first 3x3m module, and $30,000 for each module thereafter. The initial $40,000 loading was to cover costs for setting up a construction jig, and at least half the rest of the cost is taken up by labour associated with the welding process. The project was promptly discontinued as the quote came in well over budget and there was no time for further design refinement.

Follow-Up

The immediate termination of the project was a frustrating eventuation. There was little doubt in my mind that the construction process could be made more efficient and cost-effective. While little could be done with regards to the $40,000 jig (though this seemed unnecessary), without question the full-scale components could have been better conceived. The design problem can be stated as such: can a robust 3D compression assembly be formed using thin sheet material?
Initially, my thinking progressed in a simplistic manner. A first attempt to create a cheaper 3D component simply redeployed the logic from the scale model in 18mm (3x6mm) laminated timber. What occurred to me during the digital modelling process was that the flimsy nature of thin sheet material could be used to structural advantage. I reasoned that mildly curving (prestressing) sheet materials such as ply or steel could enable sturdy three-dimensional forms to be constructed.

This understanding sparked a series of investigations in cardboard (Figure C6-6d). The results of this exploratory process are two kinds of compressed component assemblies, each created using four identical intersecting planar pieces of material. The final form of each component emerges through the interplay of forces among the planar elements once assembled. To test the feasibility and stability of the resulting components, a 1:2 scale model was constructed using 3mm ply, cable ties and twine (Figure C6-6e). This prototype was found to be stable and relatively robust, suggesting that an equivalent assembly strategy could be suited to full-scale construction. Obviously this step requires further detailing and would need to be executed in more fitting structural materials such as steel sheet, stainless steel tension wire and associated hardware.

The components developed through this materially driven process of design refinement would most likely have reduced the overall cost of construction by overcoming the need for the manual welding of steel flanges. Furthermore, it is apparent that the final components would have significantly added to the aesthetic value of the original barrier design.
C7 Design Studies - Synopsis

The Design Studies section has detailed projects that I have undertaken as a way of testing an integral computational design and manufacturing strategy in which material, structural and fabrication logics are implemented as design parameters and serve to constrain early design exploration within a spectrum of rational and buildable structures and forms. The projects have differed in nature, some have been entirely speculative and thus more or less unconstrained, while others have been carried out within a practice context and have had to respond to deadlines, costing and other project pressures.

Flexible Footbridge operates as a validation of the methodology I established in the first section, and proof of concept that tensegrity structures with 3D compressed components could be deployed within a functional context. It illustrates how Struck can be used during early design exploration to test possible forms for a given tensegrity configuration, and how this data can in turn drive CNC fabrication of the required components.

(near) Instant Highrise was a design competition entry looking into rapidly deployable tensegrity structures and the notion of further optimising compression assemblies. The active model in Struck illustrated how the proposed configuration could create a variety of appealing forms through the use of varied structural members.

The Kinetic Tensegrity Grid Structures study began as a further validation of the process and exploration into how tensegrity grids with 3D compressed components could be deployed in an architectural context. The active digital model in Struck revealed that the particular grid assembly I was exploring could in fact be kinetic and potentially respond to its context by changing shape, porosity and transparency. This insight prompted a significant and otherwise impossible change in design direction.

This study is profound in that it reveals how informed computational design tools can serve to catalyse innovation and become active collaborators in the quest for better design and more streamlined production processes.

The Ouroboros collaboration demonstrates the viability of architectural scale tensegrity structures and their deployment in the public realm. In this project, extensive physical and digital calibration enabled all fabrication issues to be accounted for and appropriate construction details devised. This project illustrates how an engagement with and intimate knowledge of material systems is highly beneficial for architects wishing to achieve a fluid translation from concept to object.

The New City Vision project utilises Struck to design a 32.65 metre tall tensegrity signage tower. While the design and prototyping phases suggested the tower to be feasible, the engineering phase revealed that tensegrity structures were not compatible with conventional approaches to structural analysis. The lack of adequate analysis tools resulted in design changes that undermined the initial structural concept. This study revealed that tensegrity structures require specialist engineers capable of dealing with structural indeterminism.

Tensegrity Barrier attempted once again to deploy the approach at a large scale and in the public realm. Struck was used to explore various tensegrity configurations and demonstrate to clients how the specific configuration chosen could be deployed in different ways. This study was prematurely discontinued after an initial quote for fabrication came in over budget. The reason for this was largely due to a lack of design resolution. In a follow up study I further refined the compressed component assemblies and demonstrated how they could be robustly constructed using thin sheet materials. Ironically perhaps, this final and predominantly analogue study served to reinforce the importance of material engagement and physical calibration during design exploration and refinement.
C8 Summary

Investigation C set out to explore the implications of a mutually informed digital-material prototyping process and test whether computational design tools with embedded material intelligence can truly expand material know-how and thus help to streamline design to production processes in architecture. Building on observations from Investigation B and a desire to explore large scale fabrication, I began this applied research through an extensive physical and digital prototyping process focussed on better understanding tensegrity structures.

The first part of this chapter provided an overview of tensegrity and described my initial experimentation. This materially engaged process revealed a number of interesting and beneficial structural and compositional characteristics, but also highlighted certain limits and constraints preventing their deployment in architecture. A collaboration with structural engineers resulted in a new class of tensegrity that was demonstrated to address some of these issues.

To make this discovery relevant to my research, I required a computational approach capable of simulating their behaviour. A number of different tools, techniques and approaches were tested. A suitable methodology was found using Struck - a particle spring solver that facilitates dynamic interactions between interconnected networks of tensile and compressive members. Similar to Killian’s CADenary software discussed in chapter three, the interactive visualisation in Struck provides continuous feedback regarding material and structural behaviour. Connecting Struck to Rhino through a simple script established the basis for a generative and integral design to production workflow.

The second component of Investigation C implemented the aforementioned research within a series of architecturally focussed studies. These studies linked real time simulation and analysis with previously established material, structural and assembly logics to test an integral materially informed computational design to production process. In the next chapter I will discuss my findings and the overall implications and outcomes of my project-led research.
CHAPTER FOUR

4.1 Introduction
4.2 Research Overview
4.3 Summarising the Results
4.4 Implications and Outcomes
4.5 Further Research
4.6 Conclusion
4.1 Introduction

At the core of this research is the idea that computation and CNC manufacturing empower architects with a new set of tools and technologies, which can potentially support more informed and better integrated architectural design to production methods. This exegesis has documented my approach to exploring this proposition. The primary vehicle for investigation has been project based research and the principle contribution is identifying how the critical factors underpinning this endeavour - material engagement and better informed design representations - could be supported through an integral computation based approach.

Within this chapter I summarise the results of my applied project work, discuss the conceptual implications and outline potential areas for further research.

4.2 Research Overview

To explore the extent to which digital design tools and manufacturing technologies might facilitate more informed and better integrated ways of designing and producing architecture, I identified where this concept sits within contemporary architectural discourse and carried out three applied research investigations focussed on digitally assisted design to production across a variety of scales.

In Chapter One I introduced the topic under investigation, described my aim, motivations and detailed the design of my research.

In Chapter Two I identified that the contemporary disjunction between design and production in architecture is historically linked to a shift in design communication and an erosion of practical knowledge among architects.

I then drew on selected architectural literature to locate my research within contemporary discourse and introduced the fundamental question that this dissertation aims to address. Namely, can computation and CNC manufacturing support more informed and better integrated architectural design to production methods?

Within Investigation A I began unravelling this question via the manufacture of small scale functional objects using a combination of digital modelling, additive fabrication and traditional metal casting techniques. I found that a crucial aspect of achieving continuity from conception to production, is having a deep practical knowledge of tools, materials and manufacturing processes.

In Chapter Three I provided a context for the next phase of my applied research and furthered my understanding of how digital technologies might support a more materially informed and engaged design approach. I identified performance based design as the contemporary paradigm associated with better informed computational design methods and elaborated on selected precedents focussed specifically on material performance in architecture. Each precedent I discussed points to new ways of informing design through an integral design to production strategy in which material, structural and fabrication logics are used to constrain early design exploration within a spectrum of rational and buildable structures and forms.

Following on from this, Investigation B engaged a generative design methodology known as topology optimisation in order to explore the hypothesis that digital design representations informed by material and structural logics can better support the quest to integrate design, analysis, manufacture and assembly in architecture. While topology optimisation on its own was found to be moderately useful, this set of studies revealed that linking generative digital prototypes to material explorations via simple modelling techniques, may offer an avenue to better informed design exploration and a more coherent design to production workflow.
To build on the results of the topology optimisation research and further explore how a mutually informed digital-material feedback loop could benefit architecture, Investigation C embarked on an extensive process of physical and digital prototyping as a way of developing and implementing an integral computational design to production strategy. This investigation was centred around an intriguing family of prestressed trusses known as tensegrity structures. A series of design studies explored the feasibility of deploying such structures in architecture and tested the integral design to production workflow that was developed earlier.

4.3 Summarising the Results

My practical investigations aimed to understand how and in what ways computation and CNC manufacturing might support more informed and better integrated architectural design to production methods. Prior to initiating this research, my assumption based on literature and my own experience, was that digital technologies could potentially enable the conventional disjunction to be addressed by facilitating a ‘direct link from design to production’.

Investigation A: From Conception to Production

Investigation A was initiated as a way of testing my assumptions and familiarising myself with a suite of advanced computational design and manufacturing tools and techniques.

The process of designing and fabricating a set of functional objects using advanced technologies revealed that achieving continuity between the virtual and physical is not as reliant on direct manufacturing as one might expect. Instead this capacity was found to depend equally on two particular and interdependent features of working with digital technologies.

I identified these traits as:

- **Digital | Material Fluency** - Knowledge of relevant digital software complimented by an immediate involvement with materials and manufacturing processes.
- **Rapid Digital-Material Feedback** - The ability to rapidly cycle through numerous iterations and translations across media and materials.

My findings suggest that the goal to integrate “design, analysis, manufacture, and the assembly of buildings around digital technologies” (Kolarevic 2006: 2-3) relies substantially on practical knowledge of tools, materials and manufacturing. In doing so, Investigation A corroborates Schodek et al’s claim that, “the artistry... and craft of using CAD/CAM techniques ... demands a thorough and highly skilled knowledge of physical fabrication” (Schodek et al 2005: 122-123). Klinger agrees that implementing digital technologies in design also requires “strong design ideas, knowledge of a variety of software, and an understanding of fabrication processes” (Klinger 2002: 5). I found that fluency in digital and material processes enables rapid exploration and experimentation across a variety of media and materials, and ultimately leads to a balanced consideration of practical constraints and potentials during design exploration and subsequent refinement processes.

Investigation A revealed that engaging computation and CNC manufacturing is contingent on digital and material know-how, and that this knowledge is of significant benefit during early design exploration. It follows that implementing material, structural and assembly logics as parameters within digital design representations may potentially lead to more informed and better integrated design to production processes in architecture.
The concept of guiding early design decision making with factors typically considered downstream corresponds to research being carried out within the field of performance-based design and is particularly related to the precedents I discussed in Chapter Three focused on material performance.

Investigation B: From Product to Process

To explore the hypothesis that digital design representations informed by material and structural logics can better support integration between design, analysis, manufacture, and assembly in architecture, Investigation B investigated a generative computational design strategy that seeks the most efficient distribution of material in response to applied forces.

In a series of studies, I explored how this methodology - known broadly as topology optimisation - could be used to inform the design to production process. Initially, I assumed that linking structural form finding techniques with CNC fabrication capabilities would enable a more or less integral design to production workflow. While this was found to be true to an extent within study one, I discovered within the following studies that topology optimisation is more useful to architects as a way of generating, testing and calibrating novel material configurations.

In particular, the third study from this investigation illustrated how a rapid and genuine understanding of material and structural tendencies can be achieved through a tightly linked feedback loop between digital and physical media.

I identified three particular insights that emerged from these studies:

• **Digital-Material Calibration** - A tightly linked feedback loop between digital and physical media enables verification and expansion of computational results.

• **Rapid Results** - The speed of feedback between digital results and physical prototypes is directly proportional to the usefulness of generative tools during early design exploration and the rate at which one can develop an intuitive knowledge of material tendencies and possibilities.

• **Computer as Design Collaborator** - Utilising generative tools opens the design process to unexpected and novel outcomes that may in turn lead to increased building performance and better design.

These discoveries point to a way of supporting and enhancing a mode of architectural practice in which the logic of materials and logistics of materialisation play an active role in design outcomes and are considered from the outset of the design process. By developing a rapid and mutually informed digital-material prototyping process, feedback from one medium is able to drive further experimentation in another. This process enables results to be quickly evaluated and fed back into the next design iteration in an ever rising spiral of refinement.

The most important and unexpected result of Investigation B is that using structurally driven generative design tools in the manner just described helped to broaden and enhance material and structural understanding during early design exploration. Considering that better integrated design to production relies substantially on practical knowledge of tools, materials and manufacturing, this finding suggested that the benefits of engaging computation and CNC manufacturing during design exploration go beyond simply “merging production and design into a common language of digital information” [Marble 2010: 40]. Instead, a greater potential lies in exploring how computation and CNC manufacturing technologies could support better informed decision making during conceptual design and help to rapidly expand practical knowledge.
Investigation C: From Process to System

Investigation C was a process of discovery aimed at exploring the notion that conceptual digital design tools with embedded material intelligence may improve design outcomes and, when combined with CNC technologies, lead to enhanced practical knowledge. The initial component of this applied research focussed on an intriguing family of prestressed trusses known as Tensegrity structures. During this phase I was interested in identifying an integral computational design to production strategy that would incorporate and expand on the findings from the previous investigations, specifically by supporting rapid digital-material feedback.

The main outcomes from this part of the investigation were:

- The development of a new class of tensegrity that makes use of 3D compressed components to restrict structural kinematics and ease fabrication complexity
- Identifying an appropriate computational form finding and simulation method capable of providing immediate feedback with regards to structural integrity and material behaviour

Combining these strategies - a systems based assembly logic with a physics based simulation - allowed for an integral design to production loop, which I then tested through a series of architectural studies. Though varied, each design study sheds light on a particular aspect of the methodology I employed. As a body of work they point to new ways of informing architectural design through a tight coupling between design (synthesis) and evaluation (analysis).

While Investigation C represents a significant technical contribution to the field of structural engineering (evidenced by peer-reviewed publication in the Journal of the International Association for Shell and Spatial Structures), the primary implications for architectural practice are of a different nature (evidenced by peer-reviewed publication in the proceedings of ACADIA 2009 and ECAADE 2009 conferences).

Searching for a way to better inform design to production processes in architecture led me to discover an emerging approach to computational design representation capable of supporting a new kind of architectural design process. By linking low resolution simulation to previously established material, structural and assembly logics, I found that three things became possible:

- **Interactive evaluation and visualisation** - Immediate feedback with regards to material, structural and assembly compliance.
- **Material Intuition** - Enhanced understanding of material tendencies and potentials.
- **Custom material assemblies** - Development of novel material configurations with specific structural properties and behaviours.

In terms of my initial aims for this investigation, the foremost outcome from the design studies component was to identify how interactive representations that link digital and material media provide a powerful framework for developing insight into and conceptualising new kinds of architectural constructs. This is perhaps best evidenced by the Kinetic Tensegrity Grids study which revealed how such tools can serve to catalyse innovation and become active collaborators in the quest for better design and more integrated production processes.
It is important to note that the simulation approach I utilised was low-resolution and failed to account for important external parameters such as gravity. Calibrating and verifying digital explorations against rapid physical prototypes served to demonstrate this was not a significant limitation during early design exploration. The bidirectional feedback loop between digital and physical media was shown to address any ambiguities arising from inaccuracy of the digital simulation. Furthermore, the low-resolution and computationally lightweight nature of the Struck applet allowed for continuous and immediate structural and material feedback while enabling forces, connective logic and form to be manipulated in real-time. In this way, it became possible to verify the feasibility of one tensegrity module and subsequently test and predict the structural behaviour and formal potential of large modular aggregations. I found that this methodology expanded the spectrum of design possibilities by revealing unforeseen material potentials and facilitating the exploration of forms and structures that could not otherwise be investigated during early design exploration due to their complexity. In doing so, the approach I have described enabled me to rapidly and significantly enhance my understanding of how tensegrity structures behave in the real world and my ability to foresee their limitations and potentials.

This refinement of practical knowledge and material intuition is consistent with Kilian’s observation [mentioned in Chapter Three] that introducing interactive form finding during the early design phase could allow architects to cultivate an intuitive understanding of structural behaviour, when exploring complex forms (Kilian 2005, Kilian & Ochsendorf 2005). The creator of a recent plug in for Rhinoceros which facilitates a similar kind of user interaction suggests, “if designers can see the structural implications of the changes they make on screen in 3D as they make them, it opens up a whole new way of working” (Piker 2010: np). As my experiences throughout the design studies demonstrate, “while not a replacement for a full structural analysis, this type of feedback could over time build up the designer’s intuition for effective forms” [Ibid].

Synopsis

My practical investigations substantiate the proposition suggested by contemporary architectural commentators, that computation and CNC manufacturing can support more informed and better integrated architectural design to production methods. They reveal however, while accurate to a point, this statement is lacking at least two qualifications that appear crucial and provide an important clue as to how digital technologies could be used to fundamentally transform the relationship between design and production in architecture.

Whereas it is commonly thought that better design to production hinges on new ‘file to factory’ manufacturing potentials, my research has shown that engaging with digital technologies enables the reevaluation of two fundamental characteristics of conventional architectural practice. Firstly, computation supports alternate modes of design representation capable of communicating richer and more diverse information than traditional representational methods. Secondly, combining this with access to CNC fabrication during early design exploration enables a mutually informed digital-material feedback loop and rapid cultivation of practical knowledge to do with material potentials and construction processes.

The results from my practical work thus reveal how computation and CNC manufacturing can help to strengthen the relationship between design and production in architecture in three particular ways:

- By supporting new dynamic modes of representation capable of providing immediate analytic feedback during early design exploration
By allowing architects to gain practical knowledge through early engagement with materials and manufacturing processes

By facilitating a mutually informed digital-material feedback loop that serves to calibrate results from generative processes, enhance material understanding and guide further experimentation

Considering these findings, the central proposition of my research can be stated as such:

**Computation and CNC manufacturing can support better integrated architectural design to production methods, by facilitating a rapid and mutually informed digital-material feedback loop during early design exploration, and by supporting more informed decision making, through the use of dynamic digital representations with embedded material intelligence.**

### 4.4 Implications and Outcomes

This PhD has been undertaken in project mode. Consequently, practical work has been the central driver of my research. Complementing my applied investigations however, I have undertaken broad theoretical research across numerous scales and disciplines. This vast exploration and review of literature catalysed a plethora of thoughts and dialogues (both internal and external). As is generally the case with deep and extensive research, many of these theoretical trajectories are of only minor relevance to the primary questions and topics addressed by my practical work and described in this document.

In this section, I will discuss the more pertinent lines of thinking that have evolved through and informed my research journey. I have chosen to elaborate on these particular areas as they are related to the primary results of my research and force re-evaluation of the conventional role of the architect by pointing towards new possibilities for architecture in the digital age. An important goal of this section is to introduce and discuss the theoretical framework I have developed as a result of undertaking this research. For clarity I have divided this discussion into three broad categories that address technical, cultural and philosophical aspects of contemporary architectural discourse and practice.

**Technical Implications:**

**Interactive Simulation and Evaluation**

In Chapter Two, I described how the evolution of design representation during the Renaissance, catalysed a division of labour between designers and craftsmen. At first glance, the most obvious thing that computation and CNC manufacturing has to offer contemporary architects is an opportunity to rethink this relationship by apparently collapsing the division between designing and making via a so-called ‘digital continuum from design to construction’. My research has shown however, that beyond the ability to work directly with fabrication information lies a further and more profound possibility for architects. Namely, the potential of working with new dynamic modes of design representation capable of providing immediate feedback with regards to feasibility and performance criteria.

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1. Some of my expanded thoughts and ideas can be found in the publications I have included in the appendix.
In a paper titled Integration: Master [Planner | Programmer | Builder] (2001), Cristiano Ceccato makes a distinction between first, second and third generation design software. He suggests that first generation tools are "the electronic equivalent of physical tools such as pen and drawing board" (Ceccato 2001: 3). The second generation, which includes conventional parametric and building information modelling approaches, permit collaborative processes, complex document management and increasingly complex geometric operations and representations, but typically emulate activities that can otherwise be done manually (Ibid). The idea of third generation design software is advanced, which would promote a new kind of reciprocal relationship "where the designer and computer form a partnership of compliments, each contributing specific abilities and knowledge to the overall task of architecture" (Ibid). Ceccato argues that addressing the structured semantics of an architectural design by embedding design ‘intelligence’ "in the form of rules, gestures, goals and parameters" (Ibid: 4) within digital representations, will be of benefit by enabling architects to explore and test a vast range of plausible design solutions and variants during early design exploration.

Within Chapter Three I discussed how an analogous concept is the underlying principle behind performance based design, but that a significant limitation encountered thus far is the computationally expensive nature of high-resolution design analysis and the time taken for results to emerge (Kolarovic & Malkawi 2005, Nicholas 2008). During the conceptual phases of architectural design, "the designer’s imagination is at work to capture different design possibilities. Early design exploration is essentially a speculative process with its own dynamics, involving intuition and spontaneity" (Attar et al. 2009: 4). To compliment the rapid pace of this process, feedback from computational analysis should ideally occur in real time.

In pursuing this line of thinking I found that animation based modelling offers an important clue. Attar et al. note, "the idea of animation as simulation provides architects with an additional opportunity to explore new methods of design ideation by approaching design as a set of parameters responding to dynamic, material and variable contextual forces over time" (Attar et al. 2005: 2). Moreover, "the integration of simulation opens up the possibilities for a more dynamic framework in the early stages of design" (Ibid). Investigation C necessitated engagement with a piece of software that combined the immediacy of animation tools with analytic logic of engineering principles. The Struck applet is a preliminary example of third generation design software that expands conventional modes of design representation. This hybrid animated engineering approach enables the user to manipulate material, structural and assembly parameters and evaluate the results simultaneously, allowing design synthesis to be carried out alongside design analysis. While solutions are only approximate, I found that an ability to interact with and ‘tune’ the form of a virtual tensegrity system in real time was a fair trade-off for precise results as it revealed unforeseen material tendencies and enabled the exploration of complex aggregate behaviours that would otherwise be very difficult if not impossible to explore during early design exploration.

I would argue that obtaining rapid qualitative feedback better compliments the creative task of conceptual design in comparison to the precise but time consuming quantitative feedback that emerges from high resolution engineering analysis. Therefore, I believe Struck can be considered a precursor to more sophisticated interactive simulation and evaluation tools for architects that will integrate animation principles and engineering logic to provide continuous feedback during design development. Dynamic representations of this nature are significantly different to conventional representational tools. Moreover, as my applied research has demonstrated, their use can lead to heightened intuition and awareness of critical design to production factors, and extend the reach of the architect by enabling practical concerns to inform early design exploration in a fluid and flexible manner.
Parallel Research

There is a significant amount of parallel research that supports my technical claims, findings and ideas. I will briefly describe some of the other techniques and approaches being explored and developed within architecture and engineering communities.

• Physics-Based Generative Design

In a paper titled Physics-Based Generative Design (2009), Attar et al. describe how physics-based modelling enables the integration of two computational paradigms. Firstly it facilitates design analysis via "simulation of complex natural phenomenon" (Attar et al. 2009: 1). Secondly, it supports design synthesis by providing "an active space of progressive formation and mutation" (Ibid). The authors present a unified constraint solver for physics-based interactive form-finding and explain how "physics-based generative design represents a paradigm shift from the traditional primacy of object to an exploratory approach of investigating interacting elements, interdependencies and systems" (Ibid: 2). This research is being conducted in-house at Autodesk and is focused on developing a stable numerical model that supports rapid iterations between design and analysis. The goal of this exploration is to provide designers with "light-weight conceptual models that can be further refined in the later stages of design" (Ibid: 11).

The authors classify their examples as Collision-based (draping, wrapping, bounded growth) and Equilibrium-based (funicular type structures). The unified solver is capable of combining both approaches to achieve complex emergent behaviors (Ibid: 5). Of particular interest is their description of how such an approach might enable new modes of design rationalization. They note "Ideally the designer wants to experiment with changes in overall form and configuration [top-down] while at the same time exploring the consequence of different fabrication techniques [bottom-up]" (Ibid: 12).

In contrast to post-rationalised and pre-rationalised approaches to design materialisation, Attar et al. propose the notion of embedded-rationality to describe the integration of form exploration with material and fabrication constraints (Ibid). The paper concludes by suggesting, "simulation for design will be an enabling technology for advancing the future of computer aided architectural design" (Ibid: 13).

• Kangaroo Physics

In March 2010 Kangaroo Physics was released as a plugin for Grasshopper - a graphical algorithm editor tightly integrated with Rhino’s 3D modelling tools 2. Kangaroo is a live physics engine for interactive simulation, optimization and form-finding directly within Grasshopper [Grasshopper Website 2011: np] 3.

Daniel Piker, who is the developer, maintains a blog to keep users up to date with ongoing changes. From one of his blog entries, it is clear that the motivation behind Kangaroo is to facilitate more informed and playful architectural design exploration by integrating immediate structural feedback within a design specific modelling environment. Piker notes how typical architect - engineer interaction takes considerable time due to complexities around information transfer and software interoperability. This protracted process hinders the extent to which results from structural analysis can be used to inform conceptual design. As I mentioned earlier, Piker’s belief is that if designers can see the structural implications of the changes they make to digital models as they make them, “it opens up a whole new way of working” [Piker 2010: np] 4.

Kangaroo Physics is still in its early stages of development but has already garnered much interest from the architectural design research community. I have tested a number of tensegrity configurations in Kangaroo and found that they behave similarly to models in Struck. In addition, it has been possible to explore their behaviour under gravity and other external loads which is a significant advantage.

• **Karamba**
  
  While Kangaroo is specifically targeted towards bridging the gap between analysis and synthesis at early stages of design process, another recent plugin for Grasshopper – Karamba – aims to close the gap between parametric design and structural assessment (Karamba Website: np) 5. Karamba is a Finite Element Analysis package developed by Dr. Clemens Preisinger and Bollinger-Grohmann Schneider Engineers. It allows designers to interactively calculate and analyse the response of three dimensional beam structures under the action of external loads using Rhinoceros as the geometric platform (SmartGeometry Website 2011: np) 6.

  From the Karamba website:
  - karamba is integrated in Grasshopper and fully parametrizable.
  - karamba provides accurate analysis of spatial trusses and frames.
  - karamba comes with its own finite element analysis module.

  Corroborating previous observations, the developers suggest, “Karamba establishes an intuitive feedback loop between physical behavior and geometry that can be used to inform design decisions and form-finding” [SmartGeometry Website 2011: np].

• **Interactive Structural Analysis**
  
  In the past few years, interactive structural analysis has also become a research focus within structural engineering. An early example is an educational tool called Arcade: Interactive Non-linear Structural Analysis and Animation 7. The name suggests that one of the lessons engineers can from arcade games is “the importance of interactivity, and the ability to perform real-time, non-linear physical simulation” [Martini 2006].

  The author of Arcade, Kirk Martini, suggests that interactive analysis will not replace other methods used in structural engineering, “but has the potential to complement them, adding an important tool to the structural engineering repertoire. The potential impact is particularly important in structural education, which currently places little emphasis on the non-linear and dynamic phenomena that commonly characterise structural failure” [Ibid]. This statement once again reinforces the notion that interactive simulation tools can enable designers to refine their intuition in regards to the behaviour of particular material systems and structural configurations.

  A further example is Dr. Frame 3D, a commercial application marketed towards structural engineers. Dr. Frame 3D is developed by a company called Dr. Software, who specialise in real-time structural analysis for engineers and architects 8. It provides a “direct manipulation environment in which users can interactively build and test 3D truss and frame structures while receiving visual and numeric feedback to indicate structural behavior – all in real time!” [Dr. Software Website: np]. Additionally, investigation into high-resolution but computationally inexpensive real time simulation and analysis of linear elastic and homogenous structures is being carried out by Baudet et al. using particle spring systems (2007, 2009).

**Summary**

One way of understanding how interactive simulation and evaluation tools can meaningfully assist and potentially transform architectural design is to consider conventional word processing software. Word processing provides real-time feedback to aid with correct grammar and spelling. It is continuously checking for mistakes, which are colour-coded to communicate the type of error that has been made. One can choose to ignore the feedback, fix the mistake manually, or choose from a drop down list of possible ways around the problem.
Architectural software would be more helpful if immediate analytic feedback let architects know when physical limits (laws of physics, limits of material or fabrication process etc.) have been breached and performance criteria (environmental, structural etc.) have been more or less satisfied. Similarly to word processing, a designer might choose to ignore the feedback, fix the oversight manually, or choose from a drop down list of possible ways around the problem.

Such an approach to architectural design is exceptionally different from traditional methods that utilise static design environments (such as paper or conventional 3D modelling software) and thus rely largely on a designer’s intuition and prior experience. A more conversant kind of human-computer interaction is consistent with the visionary ideas and approaches outlined by Nigel Cross, Nicholas Negroponte, William Mitchell and others at the dawn of computing.

It is clear from research being carried out globally that there is a significant shift on the horizon for architectural design and representation methods. Considering the pivotal role that representation has played in architectural design thinking and practice throughout history, it is my belief that this latest evolution will have as significant an impact in architecture as the development of perspective drawing during the Renaissance. The rapid human-computer interaction that is facilitated through interactive simulation and evaluation methods enables intuition to quickly develop with regards to the behavioural tendencies of prospective systems under physical loading. I have illustrated how this can be beneficial for exploring structural and material systems. It is possible to extend this approach to other kinds of building loads and criteria such as thermal, acoustic, lighting, economy, etc.

Cultural Implications:

Material Practice

“Architecture as a material practice implies that making, the close engagement with material, is intrinsic to a design process” [Kolarevic 2010: 67]

Conventional architectural design methods tend to prioritise the elaboration of form over its subsequent materialization (ICD Website 2010, Ceccato 2001, Leach 2004, 2008, Oxman & Oxman 2010, Weinand & Hudert 2010). My applied research has demonstrated that critical engagement with computation and CNC manufacturing allows architects to reconsider the notion that form [or design] precedes material considerations [or making], and that these two aspects of architecture are independent. It therefore points to a digitally supported approach to design in which “materiality is actively involved in the design process” [Weinand & Hudert 2010: 107].

The conceptual implications of such an approach are best illustrated by the processes and outcomes during Investigation C. The integral digital-material feedback loop that I implemented during this investigation enabled formal and practical design decisions to be made with respect to material characteristics and feasibility. Basing my decision making on these more pragmatic factors during early design exploration prompted a definitive shift of focus beyond “the appearance of things … [towards] the deepest substance of making” [Kieran & Timberlake 2004: xi]. In other words, instead of thinking through images and drawing - or what I wanted a design to look like, I began to think about architecture through an understanding of material potentials and making - or how a design might be realised. I found that focussing more on materiality than imagery during conceptual design opened up a range of unexpected and innovative formal, material and structural possibilities that were, by their very nature, inherently rational and buildable.
This profound shift in my design thinking and practice correlates with recent cultural and theoretical discourses aimed at identifying emerging trends in contemporary architectural practices.

The editor of Material Matters: Architecture and Material Practice (2007), notes that the publication "emerges at a time when there is a renewed interest in questions of materiality in architecture" (Lloyd-Thomas 2007: 5). The phrase ‘material practice’ is used to “draw attention to what is a shared refusal to consider materials in purely visual (and static) terms and an insistence on examining materials as part of a network of forces and actions” (Ibid).

In Plans to Matter: Towards a History of Material Possibility (2007) philosopher Andrew Benjamin clarifies this idea by making a distinction between “a history of architecture that becomes the history of the plan and a history of architecture as the history of material possibilities” (Benjamin 2007: 14). The objective of his essay is to position materiality as a central theme within contemporary architectural discourse by outlining what he describes as a “move from the centrality of the plan to the materialist account of the relationship between the digital and the material” (Ibid: 25).

Similarly, in an essay titled New Materialism (2008), contemporary architectural theorist Neil Leach draws on the materialist philosophies of Gilles Deleuze and Manuel DeLanda to suggest that “the whole history of architecture can be divided into two contrasting yet reciprocally related outlooks. One would be a broadly aesthetic outlook that tends to impose form on building materials, according to some predefined ‘template’. The other would be a broadly structural outlook that tends to allow forms to ‘emerge’ according to certain [material] requirements” (Leach 2008).

By analysing the speculative work emerging out of international computational design research enclaves, and the approaches being explored by progressive architectural firms, Leach observes that among contemporary practitioners there is a growing “move away from an architecture based on purely visual concerns towards an architecture justified by its performance” (Leach 2008). Within such practices, “structural, constructional, economic, environmental and other parameters – concerns that were once relegated to the realm of secondary concerns – have become primary, and are being embraced as positive inputs into the design process from the outset” (Ibid).

Reinforcing my practical experiences and findings, Leach concludes that digitally enfranchised architects are therefore becoming less concerned with what a building might ‘mean’ or look like, and more interested in “performance and material behaviours” (Ibid).

In the seminal text A Thousand Plateaus (1980), Deleuze and Guattari offer the terms Romanesque and Gothic to differentiate these alternate modes of architectural practice. One can gather from their writing that “the Gothic is based primarily on understanding architecture in terms of materiality and structure, while the (Romanesque) is based primarily on understanding architecture in terms of visual composition” (Leach et al. 2004: 5). Deleuze and Guattari suggest that the difference between these two approaches “is not simply quantitative; it marks a qualitative change: the static relation, form-matter, tends to fade into the background in favor of a dynamic relation, material-forces” (Deleuze and Guattari 1980: 364).

This literature reinforces my personal reflections and provides a useful (albeit reductive) way of thinking about differing modes of digitally enabled architectural design. One end of the spectrum may be described as Visual Practice – “a sculpturally driven design process where the translation of form into buildable components is developed after establishing the form” (Kilian 2007: 38). Contemporary practitioners such as Frank Gehry and Zaha Hadid [among many others] can be said to employ this approach.
The other end of the spectrum can be thought of as Material Practice – a materially driven design process “based on an understanding of material systems ... as generative drivers in the design process” [Menges 2010: np]. Historical precedents for this mode of design can be found in the works of Antoni Gaudí, Frei Otto and Heinz Isler (among a handful of others). As my research attests to, exploring how computation might support material practice is currently under investigation and thus contemporary examples are generally limited to experimental constructions.

The importance of articulating these two differing yet complimentary modes of design from a cultural point of view lies in the fact that digital technologies support, and perhaps even encourage, a shift of focus during the early design phase from visual to material practice. This proposition is corroborated by Kolarevic & Klinger who observe that “new techniques and methods of digitally-enabled making are reaffirming ... long forgotten notions of craft, resulting from a desire to extract intrinsic qualities of material and deploy them for particular effect. As such, interrogating materiality is fundamental to new attitudes towards achieving design intent” [Kolarevic & Klinger 2008: 7].

In today’s digitally augmented architectural design processes, material practice could be defined as:

A materially engaged approach to design in which the logic of materials and logistics of materialisation are used to actively inform design exploration, refinement and construction processes.

Customised Material Assemblies

Investigation C revealed an exciting and unexpected by-product of approaching architecture according to my definition of material practice. I found that coupling material investigations with analogous computational simulation methods allowed me to explore material assemblies that exhibit custom properties related to specific loading conditions and desired material or spatial effects.

This finding correlates with Picon’s suggestion that “the digital landscape provides ... the possibility to design materials, to shape their properties and appearance, instead of using them in a passive manner” [Picon 2005: 120]. Likewise, Schodek et al. have argued that digital expertise “could extend the design effort to experiment, develop, and fabricate assemblies and components – and thus can expand the architect’s immediate involvement with the art of making, while allowing fabrication characteristics to be fully considered during the design phase” [Schodek et al 2005: 125]. My research into simulating, designing and constructing tensegrity structures with 3D compressed components substantiates these comments and suggests that interactive simulation and evaluation tools are an invaluable apparatus for enabling such an approach.

The Kinetic Grid study is probably the most clear and comprehensive example of how a rapid and mutually informed digital-material feedback loop can enable exploration and development of customised material assemblies. The starting point for this study was a space filling grid system derived from two specific compressed components. The aim was to explore how this particular structural configuration might be used to design and construct a freeform yet self supporting building envelope.
A coherent link between digital and physical models enabled the system to be scaled in terms of complexity. This made it possible to verify material feasibility using a single physical module and then digitally explore the emergent behaviour and form generating capacity of much larger modular aggregations. By interactively adjusting internal parameters and applying external constraints, I found that it was possible to manipulate simple geometries into a variety of complex yet rational forms.

During this process of materially driven form finding, it became apparent that the configuration I had chosen to explore behaved very much like a textile, and that the resulting forms were intimately tied to its internal connective logic and related behavioural tendencies. Since I had complete interactive control over internal structural relationships, I was able to customise the behaviour of this textile by manipulating its ‘warp and weft’ according to my design requirements. One example is the inclusion of individually controlled ‘tension’ spines across the structure that could be used to manipulate global form. Another is the addition of actuation elements that dynamically manipulate its ‘warp and weft’ according to design requirements. Since I had complete interactive control over internal structural relationships, I was able to customise the behaviour of this textile by manipulating its ‘warp and weft’ according to my design requirements. One example is the inclusion of individually controlled ‘tension’ spines across the structure that could be used to manipulate global form. Another is the addition of actuation elements that dynamically control the porosity of the grid assembly.

The idea that designers might leverage computation and CNC manufacturing to develop and deploy custom material systems is validated in a recent call for contributions to a forthcoming technology, manufacturing to develop and deploy custom material systems is validated in a recent call for contributions to a forthcoming technology, material systems for architecture while experimenting with early tensegrity systems. More recent software – discussed earlier – does support this capability.

11. Whilst Struck allows nodes to be fixed in space, as I have already noted, it is not possible to assign external forces on tensegrity configurations. More recent software – discussed earlier – does support this capability.

12. Interestingly, in the AD title Architextiles (2006) Garcia notes that Buckminster Fuller developed the concept of textiles as exemplary adaptable and flexible systems for architecture while experimenting with early tensegrity systems (Garcia 2006: 15-16).

13. Ambience ’11 will be held at the university of Boras, Sweden in November 2011.


15. A-POC (a piece of cloth) is a research project undertaken by Miyake Studio into the potential of customised garments using CNC knitting technologies.
Philosophical Implications:

Beyond Hylomorphism

The transition from visually driven modes of composition towards materially informed design necessitates a fundamental shift in world view. From a philosophical standpoint, the difference between visual and material practice lies in the way architects think about the relationship between matter, structure and form. This ideological change can be thought of as moving away from mechanistic, linear or reductive notions of cause and effect towards a machinic, non-linear and holistic understanding of complex systemic behaviours. Lloyd-Thomas observes that contemporary architects are beginning to embrace this "alternative philosophical approach which does not split the world into form and matter but instead considers it in terms of force (or energy) ... in such a view the real and the virtual, or the material and the idea are part of a continuum of potentiality and actualisation" (Lloyd-Thomas 2007: 5).

Visual practice is a product of what has been called royal, major or classical science. Manuel DeLanda has observed that this branch of scientific thinking has led to a focus on linear and equilibrium behaviour and "a view of matter as an inert receptacle for forms imposed from the outside" (DeLanda 2004: 19). Visually driven design practices reinforce Aristotle’s so-called hylomorphic account of the physical world in which "matter; or 'hyle', is given shape by form, or 'morphe'. Matter in itself is [viewed as] inert and undifferentiated; it is the servant of form and gives it presence. It does not determine form" (Lloyd Thomas 2007: 3).

According to hylomorphism, "the order displayed by material systems is due to the form projected in advance of production by an external producer, a form which organises what would otherwise be chaotic or passive matter" (Protevi 2006: 296). The hylomorphic model of conception and production therefore emphasises "the image of the architect as a kind of mythic form giver" (Lloyd Thomas 2007: 5).

In A Thousand Plateaus (1980) Deleuze and Guattari develop what has been referred to as a non-hylomorphic or 'artisanal' theory of production by drawing on so-called nomad, minor or complexity sciences (Protevi 2006). Instead of focussing on linearity, equilibrium and the imposition of order, this more recent branch of scientific thinking acknowledges non-linearity and far from equilibrium conditions as being central to the self-organisational logic of matter-energy. The matter-energy continuum is viewed as possessing a kind of 'swarm intelligence' that can be exploited to help inform human actions and facilitate the 'emergence' unexpected and beneficial behaviours. According to this logic, "forms are developed by artisans out of suggested potentials of matter rather than being dreamed up by architects and then imposed on a passive matter. In artisanal production, the artisan must ... 'surrender' to matter, that is, follow its potentials by attending to its implicit forms, and then devise operations that bring forth those potentials to actualize the desired properties" (Protevi 2006: 296). In the words of Deleuze and Guattari, "it is a question of surrendering to [a specific material] ... then following where it leads by connecting operations to a materiality, instead of imposing a form upon a matter" (Deleuze and Guattari 1980: 408).

In the essay Material Complexity (2004), Manuel DeLanda describes how "artisans, craftsmen and minor scientists in general ... always had a different conception of the relation between matter and form ... they did not impose but teased a form out of an active material, collaborating with it in the production of a final product rather than commanding it to obey and passively receive a previously defined form" (DeLanda 2004:19). He suggests that among architects, "historical processes of homogenization and routinization have promoted the 'hylomorphic schema' as a paradigm of the genesis of form. Conversely it is partly thanks to the new theories of self-organisation that the potential complexity of behavior of even the humblest forms of matter-energy has been revealed" (Ibid. 21).
DeLanda points towards a new paradigm of architectural thinking prompted partly by this alternate understanding of the relationship between energy, matter and form, and partly by the capacity to digitally model and simulate increasingly complex systems and interactions. Rather than considering matter as an inert receptacle for preconceived design ideas, progressive architects are beginning to understand that materials are active and exhibit a degree of self-organisational intelligence. Instead of forcing matter to adhere to a preconceived design vision, the logic of materials can be embedded within computational design tools such that architecture can emerge as a negotiation between intrinsic material, structural and assembly constraints and extrinsic factors such as design intent, function, environment, budget etc. By identifying the self-organising principles inherent to material systems, and implementing these as parameters within digital tools, architectural form can thus “come from within matter and not be forced upon it from without” [Teja Bach 1995: 24].

This approach to design, which combines computation with what I have identified as material practice, enables architects to “think about the origin of form and structure, not as something imposed from the outside on an inert matter … but as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create” [ibid].

A Return to Craft?

This shift in design philosophy brings with it a change in design attitude. By considering architectural form as an expression of material behaviours rather than as an expression of one individual’s ‘creative genius’, the job of the architect becomes a somewhat more humble and grounded practice.

Teasing out and exploiting the inherent characteristics of materials16 implies a methodical, iterative and highly engaged process that has resonances with the concept of craft.

Renzo Piano has suggested, “an architect must be a craftsman. Of course any tools will do; these days, the tools might include a computer, an experimental model, and mathematics. However, it is still craftsmanship – the work of someone who does not separate the work of the mind from the work of the hand. It involves a circular process that takes you from the idea … to a construction, and from a construction back to idea” [Piano 1992].

Kolarevic suggests that within today’s digitally augmented architectural practices, “craft could be understood as a set of deliberate actions based on continuous, iterative experimentation, error, and modification that could lead in the end to some innovative, unexpected, unpredictable outcome to be discovered in the intertwined processes of conception and production” [Kolarevic 2010: 73].

I have shown how interactive simulation and evaluation environments enhance this mode of operation by facilitating a “united “thinking and doing” process, which integrates the engineering, design, and fabrication disciplines in its exploration of form, performance, materials and methods” [Schodek et al. 2005: 35]. I have also demonstrated how this kind of experimental methodology demands a highly attentive mode of material engagement combined with “deep knowledge of the processes, tools and techniques, just as it did in the pre-digital era” [Kolarevic 2010: 73] 17.

16. In the case of today’s digitally mediated architectural practices, the concept of material might be extended to what could be called immaterial materials such as software, code syntaxes, scripts and emerging manufacturing platforms among other things. Similarly to physical materials, these non-physical entities have inherent material logics that serve to constrain how they are used. An extensive discussion of this however is beyond the scope of my research.

17. It should be noted that this attitude and skill is not only useful for exploring material constructs, it can also be transferred to identifying particular logics (pertaining to material, environment, structure etc) and encoding them as parameters within digital design representations.
4.6 Further Research

The research I have undertaken over the course of my candidature could be extended in at least two ways:

Multiple Criteria Simulation and Evaluation

Interactive simulation and evaluation could be expanded to include criteria other than those associated with structure, materials and assembly. Within such a system, factors to do with materialisation could provide a framework over which other performance-based analytic overlays could be superimposed.

A preliminary implementation of how this kind of design environment might function is illustrated in a software demo by architectural design firm Proxy 18. Their “Future of Architecture Software” (2008) is implemented using Processing and demonstrates how a force directed graph system built on particle-spring logic could be used to integrate iso-surfacing, analysis of implicit areas/volumes and preliminary performance evaluation (solar analysis) in a real time interactive environment. Each feature is embedded within a module that can be turned on or off accordingly.

A further similar example underpinned by force directed graph logic is a standalone educational program for windows called Graphemes, developed by Kajima Sawako and Michalatos Panagiotis (Sawapan). Graphemes is based on graph theory and a dynamic particle-spring model. According to the developers, “It has two main functions. First, the design of 2 and 3 dimensional structures through the use of topological operations where the emphasis of the interface design is on connectivity of nodes ... The second function of the program is to try and develop the structural intuition of the user by providing fast structural analysis of the design system.

Hence one can observe in near real time how changes in the connectivity graph of a space frame affect its structural behaviour” (Sawapan Website: np) 19. Structural analytics (moment diagrams, bending stresses, types of force) can be superimposed to provide useful design feedback. Upon using the software, it is easy to imagine how other modules pertaining to environmental analyses could be added and superimposed over the skeletal particle-spring network.

Graphemes provides an early example of design tools in which the synthesis/analysis cycle could be integrated via computation. The interactive and force-dependent nature of the geometry provides a powerful parametric modelling approach that enables topological relationships to be edited on the fly and an embedded logic relating to materials, which could be extended to other performance-based criteria.

Tensegrity

My research and development of tensegrity structures with 3D compressed components has already catalysed interest from within architecture and engineering communities, and is cited in recent literature exploring new tensegrity configurations and approaches to materialisation (see Appendix for full list).

Whilst there remain analysis complexities that limit the extent to which tensegrity assemblies can be deployed as a primary structural system in building and construction, my research suggests there are nevertheless some worthwhile and promising architectural applications. In particular, tensegrity structures with 3D compressed components appear to be excellent candidates for developing responsive architectural systems as demonstrated by the Kinetic Grid Structures study.


Such an approach could be used to develop energy aware building envelopes capable of dynamically modulating sound, light and heat by altering porosity, transparency and perhaps most impressively shape.

A powerful aspect of tensegrity is scale invariance as described earlier. This means that the basic principles can be applied across scales and between disciplines. Applications of tensegrity systems with 3D compressed components beyond the field of architecture include:

- New kinds of ‘soft’ mechanisms for industrial robotics
- New kinds of prosthetics that could better simulate and even extend the mobility of the human body
- New kinds of macro, micro and nano-material constructs capable of exhibiting differentiated material properties across an integrated and uninterrupted assembly.

4.5 Conclusion

The PhD research I have undertaken affirms that computation and CNC manufacturing can indeed support more informed and better integrated architectural design to production methods. Within both academic and practice-based contexts, I have demonstrated how this endeavour is specifically made possible by new interactive modes of design representation capable of facilitating a tight link between physical and digital media during early design exploration.

My research has not adhered to, or tested, one particular method or process for achieving continuity between intention and execution in architecture. Rather it has been allowed to evolve through three diverse investigations that have each had the same goal in mind. Although varied in their nature, the insights gained from each investigation have contributed to my overall understanding of how digital technologies can strengthen the relationship between design and production in architecture.

The action research methodology I adopted is very much in line with the cultural and philosophical implications of my work. Instead of implementing a predetermined series of projects looking at specific techniques, each investigation was devised and carried out in response to findings from prior practical work and complimentary theoretical explorations. This approach has allowed me to move beyond my original hypotheses and ideas, towards an unexpected result that addresses my inquiry in a more comprehensive manner than I could have imagined prior to undertaking this research.

At the outset, my assumption based on literature and my own experience was that digital technologies could potentially address the gap between intention and execution in architecture by facilitating a ‘direct link from design to production’. I pursued this notion during Investigation A and partly within Investigation B. My applied studies revealed that so-called ‘file to factory’ methodologies are useful to a degree, but that the potential of digital tools and technologies to support better integrated design to production extends far beyond the capacity to facilitate a ‘seamless’ translation between concept and object - which can sometimes be counterproductive during early design exploration.

My initial engagement with computation and CNC manufacturing revealed that the degree of integration that can be achieved between designing and making is directly proportional to the point at which materials and processes of making are considered within the design process. This finding, and an analysis of selected performance based design precedents in Chapter Three, helped me to understand that the power of digital technologies lies not in their ability to support increasingly complex visions for architecture, but rather in the possibility of facilitating ‘intelligent’ design methodologies capable of better integrating the virtual world of thoughts and ideas with the physical world of materials and making.
Within the constraints and limitations of my research, I pursued this notion to its utmost extent during Investigation C. I demonstrated how an interactive materially informed simulation and evaluation environment can rapidly enhance material understanding by providing meaningful real time feedback with regards to the behaviour of complex material systems. I calibrated these digital explorations against physical prototypes produced with the assistance of CNC technologies. In doing so, I showed how it is possible to implement a rapid and mutually informed digital-material feedback loop that in turn enables an evolutionary dialogue to emerge between designer and computer.

Through the design studies component of Investigation C, I then illustrated how this mode of interaction offers a powerful framework with which to integrally conceive and materialise architectural designs that go beyond conventional design solutions by facilitating new design opportunities and posing new challenges.

It can be concluded, rather than simply providing a means to directly integrate design and production via so-called ‘file to factory’ methods, digital technologies can offer a greater and perhaps more enduring opportunity to architects by strengthening the relationship between design and production in three important ways:

- By facilitating new dynamic modes of representation with embedded material intelligence and capable of providing immediate analytic feedback during early design exploration
- By allowing architects to rapidly gain practical knowledge through early and close engagement with materials and manufacturing processes
- By supporting a mutually informed digital-material feedback loop that serves to calibrate results from generative computational processes, enhance material understanding and guide further experimentation

In considering how the results of my research serve to inform and transform architectural design and discourse, I elaborated on implications related to technical, cultural and philosophical aspects of architectural practice. In doing so, I aimed to shed light on the ways in which my research contributes to re-evaluating the conventional focus and role of the architect.

I outlined a technical shift away from static modes of design representation towards dynamic digital representations with embedded intelligence and discussed how new kinds of interactive simulation and evaluation tools enable practical concerns to actively inform early design exploration in a fluid and flexible manner. I explained how this capability leads to heightened intuition and awareness of critical design to production factors, thereby extending the reach and effectiveness of the architect. I then elaborated on emerging parallel research that embodies similar ideas and principles.

Reflecting on my own practice and recent literature, I noted that engaging computation and CNC manufacturing in a critical manner prompts reconsideration of the convention that form (or design) precedes material consideration (or making). I suggested that digital tools - in particular those capable of better bridging between virtual and physical dimensions - are facilitating a significant cultural shift away from visually driven modes of composition towards material practice - an approach to design in which “materiality is actively involved in the design process” (Weinand & Hudert 2010: 107).
An unexpected and exceptionally promising by-product of approaching architecture in this manner is the potential for architects to address and accommodate specific design and performance criteria by using interactive simulation and evaluation to aid in the development of customised material systems. Exploiting such tools makes it possible to experiment with the internal connective logic of complex virtual or ‘pseudo’ material assemblies. This process enables discovery of new kinds of physical mechanisms and structures capable of exhibiting differentiated behaviours and properties across an integrated and uninterrupted assembly.

Lastly, I identified how the transition towards materially informed design catalyses a fundamental shift in design philosophy, in which “the static relation, form-matter, tends to fade into the background in favor of a dynamic relation, material-forces” (Deleuze and Guattari 1980: 364). According to this mode of thinking, architectural form is not an expression of one individual’s ‘creative genius’, but rather must be ‘teased’ out of materials by artisans, as a negotiation between intrinsic material properties and extrinsic factors.

I concluded by suggesting that this process prompts a highly attentive mode of material engagement that has resonances with notions of craft - “a set of deliberate actions based on continuous, iterative experimentation, error, and modification that could lead in the end to some innovative, unexpected, unpredictable outcome to be discovered in the intertwined processes of conception and production” (Kolarevic 2010: 73).

My research demonstrates that computation and CNC manufacturing technologies enrich and expand the capacities of architects by enabling an accelerated feedback loop between design synthesis and design analysis. The ability to rapidly simulate, evaluate and calibrate material behaviour enables more informed and better integrated design to production by supporting and enhancing what can be described as material practice - a materially engaged approach to design in which the logic of materials and logistics of materialisation are used to actively inform design exploration, refinement and construction processes.

A mutually informed digital-material feedback loop makes it possible to conceive and deploy new kinds of architectural material systems and materialisation strategies, which could ultimately lead to better use of available resources, more innovative architectural design and a stronger bond between design intent and built outcome, through more streamlined design to production processes.

My project work not only serves as the vehicle of discovery and evidence for this claim, I believe it also reinforces the more prosaic comment that “there appears to be something remarkable in the interaction of ... material and ... [form] that produces a distinguished quality of design ... It is perhaps the elevation of materiality to a level of prominence in design and design research that can explain this intellectual resonance and its implications for architecture as a material practice” (Weinand 2010: 107).


"317"


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i. Publications
ii. Citations of my Work
iii. Exhibitions
iv. Teaching
v. Competition Panels
vi. Full Articles
i. Publications


Frumar, JA 2007, Code To Craft – Beyond the Voxel, Proceedings of the AASA Conference, University of Technology Sydney, Australia.


ii. Citations of my Work


iii. Exhibitions

2006
- Sherman Galleries, Sydney
- 2nd Beijing Architecture Biennale

2007
- New Craft Future Voices Conference, University of Dundee, Scotland
- Yellow Brick Road, Greenwood Gallery, Melbourne
- Homo Faber: Modelling Ideas, Museum Victoria, Melbourne

2008
- Homo Faber: Modelling, Identity and the Post Digital, Museum Victoria, Melbourne
- 11th Venice Architecture Biennale

2009
- Maitreya Festival, Melbourne
- Make It Work: Engineering Possibilities, Center For Architecture in New York
- Dessa Architecture Gallery, Ljubliana, Slovenia
- Nascent Present, State of Design Festival, Melbourne
- Boys and their Toys, LOT Gallery, Kentucky USA

2011
- Surface Pop, Melbourne
- Earth, Sea, Sky, Greenwood Gallery, Melbourne
- 1000 Pound Bend, Melbourne
- Pin-up Gallery, Melbourne

2012
- Rainbow Serpent Festival, Melbourne
- 13th Venice Architecture Biennale

iv. Teaching

2006
- Liminal, RMIT Design Studio, Co-taught with Andrew Maher
- Too Liminal, RMIT Design Studio
- Building Binary, RMIT Communications Seminar
- Integrated Fabrication, RMIT Communications Seminar, Co-taught with Tim Schork

2007
- Future Systems, RMIT Design Studio, Co-taught with Kris Green
- FabHab, RMIT Design Studio, Co-taught with Tom Kovac
- FabHab 2, RMIT Design Studio, Co-taught with Tom Kovac

2008
- FabHab 3, RMIT Design Studio, Co-taught with Tom Kovac
- Langspan Highrise, RMIT Civil Engineering Elective, Co-taught with Dr. Saman DeSika and Professor Mike Xie
- Extremes, RMIT Design Studio, Co-taught with Tom Kovac

2009
- Extremes 2, RMIT & De Angewandte Design Studio, Co-taught with Tom Kovac, Wolf Prix, Reiner Zettl, Niels Jønkhans and Farzin Lofti-Jam
- Langspan Highrise, RMIT Civil Engineering Elective, Co-taught with Dr. Saman DeSika and Professor Mike Xie

2011
- Off The Shelf, RMIT Design Studio
- Off The Shelf 2, RMIT Design Studio

2012
- ART(ificial) LAb(yrinthscapes), RMIT Landscape Architecture Design Research Seminar, Co-taught with She Haker
- Headspace, Monash University Design Studio
- Production of Digital Space, Melbourne University Masters Design Studio, Co-taught with Dr. Marcus White, Daniel Fink and Dave Lister
- Studio Air: Melbourne University Undergraduate Design Studio, Co-ordinated by Stanislav Roudavski
v. Competition Panels
INSTANT HIGH-RISE
rapid infrastructure deployment

Traditionally, the infrastructure we are familiar with is permanent, linear and custom-built for specific purposes. This project re-imagines this initial form to create a flexible and versatile system that can be deployed quickly and easily.

The project uses a modular framework that allows for easy assembly and disassembly. The system is designed to be highly adaptable, allowing for a wide range of uses and applications.

The project also incorporates a system for rapid deployment, allowing for quick installation and removal. This system is designed to be highly efficient, minimizing waste and maximizing resources.

The project is intended to be used in a variety of situations, including disaster relief and humanitarian aid. It is designed to be scalable, allowing for adaptation to different situations and environments.

In conclusion, the INSTANT HIGH-RISE project represents a new way of thinking about infrastructure deployment. It is designed to be flexible, adaptable, and efficient, allowing for quick and effective deployment in a variety of situations.
vi. Full Articles
The integration of digital design tools in teaching, learning and practice over the past decade transformed the paradigm traditionally associated with design, fabrication and construction. Digital tools and technologies bridge the representational divide between conception and realization, empowering architects to regain control of the fabrication process to develop complex and holistic solutions to complicated problems. These technologies have the potential to extend human knowledge and the ‘vocabulary’ we use to engage and express ourselves.

Digital tools are prevalent in many aspects of contemporary global culture, streamlining and automating complex and tedious tasks. They are increasingly instrumental for developing complex and holistic solutions to complicated problems. These technologies have the potential to extend human knowledge and the ‘vocabulary’ we use to engage and express ourselves.

1 Introduction

Digital tools are prevalent in many aspects of contemporary global culture, streamlining and automating complex and tedious tasks. They are increasingly instrumental for developing complex and holistic solutions to complicated problems. These technologies have the potential to extend human knowledge and the ‘vocabulary’ we use to engage and express ourselves.

The advent of CAD (computer-aided design) and CAM (computer-aided manufacturing) has challenged the paradigm traditionally associated with design, fabrication and construction. CAD/CAM tools enable the direct fabrication of a virtual 3D model using a diverse range of materials and techniques. As such, these technologies bridge a representational divide between digital design and fabrication. Highly integrated in the fields of aerospace, automotive, industrial and nautical design, the use of CAD/CAM has only recently prompted interest from the architectural industry and has been adopted by various architectural practices across the globe. These professions are poised for change as they become empowered through a nascent medium where representation and fabrication information converges.

The integration of digital design tools in teaching, learning and practice over the past decade has rendered CAD obligatory as a drafting aid in much of the architecture and engineering industries. Recently, increased computing power has enabled CAD tools to mature and suggest possibilities far beyond their origins. Those at the forefront of research-based architecture practice have recognized the potential of appropriating an array of computation and fabrication strategies to extend design, manufacturing and construction capabilities.

Abstract

The digital nature of post-industrial societies has profound implications for architectural design, documentation and construction. Digital tools and technologies bridge the representational divide between conception and realization, empowering architects to regain control of the fabrication process to develop complex and holistic solutions to complicated problems. These technologies have the potential to extend human knowledge and the ‘vocabulary’ we use to engage and express ourselves.

Keywords: architecture, craft, craftsmanship, component manufacturing, computer aided manufacturing, digital design, jewelry, metal casting, rapid prototyping.

1 Introduction

Digital tools are prevalent in many aspects of contemporary global culture, streamlining and automating complex and tedious tasks. They are increasingly instrumental for developing complex and holistic solutions to complicated problems. These technologies have the potential to extend human knowledge and the ‘vocabulary’ we use to engage and express ourselves.

The advent of CAD (computer-aided design) and CAM (computer-aided manufacturing) has challenged the paradigm traditionally associated with design, fabrication and construction. CAD/CAM tools enable the direct fabrication of a virtual 3D model using a diverse range of materials and techniques. As such, these technologies bridge a representational divide between digital design and fabrication. Highly integrated in the fields of aerospace, automotive, industrial and nautical design, the use of CAD/CAM has only recently prompted interest from the architectural industry and has been adopted by various architectural practices across the globe. These professions are poised for change as they become empowered through a nascent medium where representation and fabrication information converges.

The integration of digital design tools in teaching, learning and practice over the past decade has rendered CAD obligatory as a drafting aid in much of the architecture and engineering industries. Recently, increased computing power has enabled CAD tools to mature and suggest possibilities far beyond their origins. Those at the forefront of research-based architecture practice have recognized the potential of appropriating an array of computation and fabrication strategies to extend design, manufacturing and construction capabilities.

2 Beyond Aggregates

As data driven CAM technologies increase in scale they can be used to fabricate components suitable for building and construction. Scholok outlines a host of architects and projects that have made headway into automated fabrication and rapid construction techniques for geometrically complex non-standard architecture. It is interesting to observe however that the majority of work thus far considered in this category has been surface-oriented with traditional systems manifest as sampled 2.5D instances of a particular 3D ‘master geometry’. Achieving a precise (re)production of complex digital form has consistently posed fabrication and construction challenges. Generally, so-called smooth or non-planar geometries have been accomplished with a combination of CNC (Computer Numerically Controlled) milling and casting/forming (glass, composites, plastics, concrete, metal etc) but have remained in the domain of surfaces and/or surface treatment. Bernard Frank's BMW Deutschland Pavilion built for the Frankfurt motor show in 1999 exhibits two of the dominant approaches to the construction of non-standard architectural elements: 3D doubly curved panels. Plassig panels enclose an aggregate system of intersecting planar sections that define the structure and interior. In his essay Bluring the Lines, Andrei Chazsair queries a pivotal characteristic of contemporary and emerging architectural design, fabrication and construction.

"Will CAD eventually be able to produce fully 3D forms in building scale elements or will complex forms continue to be made from 2D elements assembled into 3D aggregates?" (14)

This is an important question. It suggests thinking beyond surface to increasingly efficient and context-specific systems. CAD/CAM tools enable the direct fabrication of a virtual 3D model using a diverse range of materials and techniques. As such, these technologies bridge a representational divide between digital design and fabrication. Highly integrated in the fields of aerospace, automotive, industrial and nautical design, the use of CAD/CAM has only recently prompted interest from the architectural industry and has been adopted by various architectural practices across the globe. These professions are poised for change as they become empowered through a nascent medium where representation and fabrication information converges.

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Complex forms are increasingly frequent in the contemporary architectural lexicon and these necessitate novel and innovative means of communication. Concurrently, commercially available and emerging CAM technologies facilitate new geometric potentials and bypass the need for traditional 2D drawings to specify 3D relationships, dimensions and other vital fabrication information. This digital convergence of representation and production embodies one of the most important opportunities and challenges facing the contemporary architecture industry.
3 Case Study

3.1 Genome Jewelry – integrating digital fabrication

The Genome jewelry collection demonstrates some of the benefits that can be gained by integrating current and emerging digital technologies with traditional metal 'investment' casting. In particular, the appropriation of computation, design and fabrication strategies across scales and between disciplines.

Elastic membranes exhibit elegant and efficient solutions to spatial and structural design. These 'minimal surfaces' are curiosities that have intrigued mathematicians and designers alike and are recognized for their abilities to rationalize highly complex boundary conditions. The pioneering work of Frei Otto, Otto Steiglitz and more recently that of Ingenhoven Overduin & Associates, UN Studio and Minifie Nixon Architecture exemplify the use of these surfaces in building design and construction. Genome jewelry and its associated research began as an investigation into the use of digitally generated minimal surfaces as an architectural design tool. The Surface Evolver written by Professor Kenneth Brakke (Department of Mathematical Sciences, Susquehanna University) is a digital tool that emulates the mathematics and behavior of surfaces. This software enables the generation of unique complex forms and geometries across a variety of scales. Using Surface Evolver alongside a combination of 3D modeling packages, the Genome collection has been meticulously crafted as a comprehensive data set containing all necessary fabrication information. A high-resolution SFF system was used to produce the virtual model as a wax object. The 'printed' master was then translated into intricate preforms using a common method of investment casting. The industry contacts involved in the process are intrigued by a fresh complexity and the challenge it represents to traditional methods of manufacturing. The information exchange throughout this research has prompted reevaluation of craftsmanship and successfully demonstrates a specific contemporary process with potentials to spatial and structural design.

Digital environments enable the concurrent generation of design and manufacturing information. The complex, intricate and specific geometries explored in the Genome collection were manufactured without the use of 2D information. The final forms, a physical reproduction of precisely crafted 3D data. Beyond the implications of liberating design, digital tools and technologies question the very nature of representation and construction. This research resonates with current and future potentials for the architecture, engineering and construction industries.

Prior to the late nineteenth century, the primary metal used in construction was iron. The flexibility and strength of cast iron fixed designers to create new structural forms impossible in stone. Despite its innovation and potential, the tradition of casting metal structural elements with complex geometries has struggled during recent history. The mass-production of rolled and extruded steel from the late nineteenth century has ultimately led to the standardization of construction methods. Twentieth century industry has developed more efficient casting techniques and better-suited construction materials, however the difficulty and primary expenses involved in casting processes have always been the production of tools, patterns and molds. Casting has therefore developed into a specialized craft primarily used for its scale and suitability to mass-production. Rotheroe’s research shows that digital fabrication techniques provide a vital framework to alleviate some of these limitations, engaging concepts of mass-customization and enabling the economic manufacture of unique non-standard casting tools. By appropriating, mastering and integrating digital fabrication with design and manufacturing strategies across scales and between disciplines, Genome jewelry challenges traditional notions of craftsmanship and successfully demonstrates a specific contemporary process with potentials to spatial and structural design. The Genome designs debuted in 23 @ Sherman Galleries Sydney 2006 and have since been exhibited at the Kunst Museum Germany, 2nd Architecture Biennale Beijing and New Craft Future Voices Conference Scotland.

4 Case Study

4.1 Evolutionary Plasticity – context-specific structures in architecture

When modern man builds large load-bearing structures, he uses dense solids; steel, concrete, glass. When nature does the same, she generally uses cellular materials: wood, bone, coral. There must be good reasons for it.

Prof. M. F. Ashby, University of Cambridge

Nature always achieves its objectives economically, with the minimum energy, conserves its resources and completely recycles its waste. http://www.daimlerchrysler.com/

The success of the Genome jewelry investigation has prompted further exploration into digital means of design and fabrication at larger scales. Evolutionary Plasticity is being undertaken as research into the suitability of SFF and CNC technologies as indirect manufacturing tools for large-scale components that can be used in the architecture, engineering and construction industries. Specifically this study looks at combining traditional metal casting methods with contemporary digital fabrication to enable the economic production of molds, tools and patterns for the indirect manufacture of non-standard, geometrically complex architectural components. It is expected this production methodology will be widely applicable to the architecture and construction industries by facilitating ‘fully 3D forms in building scale elements.’ To test this idea, a computational process has been guided to generate optimized, context-specific structural forms that challenge traditional modes of fabrication.
Naturally occurring structures such as trees, bone, coral, sponge, foams and bio-mineralized prototroph shells exhibit morphologies that simultaneously negate several environmental constraints with minimal energy and material consumption. This negotiation of contextual factors achieves a near uniform stress distribution throughout the structure. The Axiom of Uniform Stress is a phrase coined by theoretical physicist, Professor Claus Mattheck to describe the adaptive growth strategy of naturally occurring self-optimizing structures. Trees have the ability to add material in order to compensate for differentiated environmental stresses. Bones can further restructure material deposits to accommodate temporal changes to their environment. Computational compilation techniques such as Bi-directional Evolutionary Structural Optimization (BESO), the similar Extended Evolutionary Structural Optimization (EESO) and Soft-Kill Option (SKO) are tools for removing low stress regions and adding material to high stress areas of a 3D digital model under specified loading conditions including consideration of scale, topology and material properties. The BESO algorithm is written by Dr. Xiaodong Huang from the Innovative Structures Group at RMIT University and extends the concept of Evolutionary Structural Optimization (ESO) initially presented by Professors Mike Xie and Grant Stevens in 1992 at the International Conference on Computational Engineering Science in Hong Kong. BESO iterates a virtual model toward uniform stress. The framework for the original BESO model is a set of basic parameters distilled from context analysis. These manifest as preliminary geometry, domain scale, load cases, boundary conditions and other design properties such as fixed areas. Adjusting and restructuring material distribution can achieve a reduced consumption and increased overall stress-to-weight ratio. This process can be applied at numerous scales and enables the evolution of optimized macrostructures and substructures and microstructures suited to lightweight context-specific building components. The resulting geometries exhibit an elegant combination of function, form and efficiency.

The design context for Evolutionary Plasticity is a popular local music venue where an obtuse concrete column interferes with privileged views toward the performance stage. Removal altogether is prohibitively expensive. Replacing it with an optimized porous structure could ease much of the visual interference and provide a functional, intriguing and interactive replacement. At this point the objects pictured are conceptual, demonstrating three possibilities for engaging the BESO algorithm to generate optimized structural systems. A contextual survey is necessary to function as the exact computational parameters to ensure the desired design outcomes are attained. Illustrated are potential macro, sub and micro-optimization schemas that can be applied to achieve enhanced strength to weight ratio components that combine a material elegance with functional and structural logic. The macrostructure accomplishes a seamless fusion with plane surfaces and illustrates a way of integrating standardized structural systems. The resulting geometry of the substructure optimization acts to enhance rigidity similar to the internal structure of bones. The internal bracing becomes dense in areas of high load transference, adding interest and differentiation to an otherwise smooth form. This optimization scheme can be used to create integrated reinforcement and framework for complex cast composites as it generates hollow sections. The filigree microstructure shows a further level of optimization at the level of surface. For current purposes the structural logic has been adapted from the deep-sea sponge Euplectella aspergillum also known as the Venus flower basket. The sponge is made of very fine silica material and though inherently brittle, has a particularly robust structure due to its uniquely integrated cross-bracing system. The natural and evolutionary structural systems demonstrate the principle of clean construction, using minimal energy and material to function optimally. The building and design industries must capitalize on recent advances in digital technologies that can be integrated to achieve leaner construction methods. Beyond minimizing energy and material consumption, digital tools can be utilized to dramatically streamline the construction process reducing waste, assembly time and on-site labor.

The resulting complexity of evolutionary-based form finding amplifies the need for new and innovative manners of fabrication. The level of detail attained in the microstructure optimization is currently only achievable in functionally architectural elements by employing an analogous fabrication process to the one used in the Genome jewelry research. As the examples shown, achieving highly optimized architectural componentry is possible by integrating digital technologies with traditional freedom manufacturing processes such as casting. Similar to the Genome jewelry, the plaster models pictured have been directly fabricated from a virtual 3D model using the 2-Corp Spectrum, a typical SFF system. The 2-Corp system also supports a proprietary starch material engineered for the investment casting process. It is expected that subdividing the final object will enable a full-scale pattern to be produced via this method. This pattern could then be used as the investment for casting a “fully 3D” building scale component in a variety of materials.

The next stage of Evolutionary Plasticity looks at viable methods of integrating specific digital fabrication and metal casting technologies. Of particular interest are investment, sand and ‘lost foam’ casting. Their differences are marked and range from size and weight limitations to part complexity constraints. The most promising and recent method is ‘lost foam’, a healthy mix of iron and sand investment casting. A sacrificial pattern generally made of polystyrene is embedded in a sand and feeder channels attached. Molten metal is poured directly into the sand, melting the foam as it takes shape. This casting method can be used for components up to 50 tons and poses little limit on form or complexity.

4.1.1 A note on aesthetics: The illusive reduction of irrelevant material using evolutionary-based computational processes returns architecture to its modernist musings. By distilling objects according to functionalist principles are we not effectively practicing modernist theory in an evolutionary fashion? Is it not ironic that the resulting forms are exceptionally flamboyant, challenging traditional methods of fabrication and the industrial ideology of mass-production? Fortunately and auspiciously, the actualization of ‘fully 3D’ non-standard, context-specific, optimized strength-to-weight ratio components is a viable prospect in post-industrial digital societies.
Conclusion

The digital revolution has heavily impacted architectural thought, research and practice. The contemporary vocabulary of digitally based architecture and practice emerged during the mid-nineties and heralded a new era of forms and form finding. This work challenged the profession, questioning traditional notions of design, manufacturing and construction. Its legacy is fundamental to the development of a new cultural aesthetic. As suggested by Chaszar, it is time to look beyond the surface of architecture to increasingly efficient and context-specific "fully 3D" structural systems that suitably complement digitally generated architectural forms. The coming generation of architects are increasingly conversant in digital design tools, however a knowledge gap emerges when considering fabrication techniques for complex geometries. The convergence of representation and production information in the digital paradigm signifies a crucial opportunity for architecture. Information-driven modeling enables associative and/or explicit 3-Dimensional models with embedded data sets that can drive computer aided manufacturing tools. As illustrated by the included case studies, active exploration and understanding of available and emerging technologies coupled with an intimate, first-hand knowledge of tools and materials evolves the role of the architect as a documentation provider toward the notion of Master data craftsmen, facilitator of the design, fabrication and construction processes.

References


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NOTE: All images appearing in this document are the work of the author.
1. Introduction

Negotiating design and performance with engineering and fabrication has been one of the central topics of contemporary architectural discourse. Driving the discussion is a growing awareness of ecology and sustainability as global goals. How does this new paradigm differ from the traditional mainstream narratives of the architectural energy metabolism and resource-driven economy? Searching for solutions has revived interest in the synthesis of natural forms as a model for architectural design.

To engage the principles of natural systems for use beyond the metaphor, we are required to develop different ways of thinking and different ways of modeling. To transmute into emergent processes of morphogenesis into abstract models for use in architecture, we require a thorough understanding of the principles that underlie natural formations. What governs the arrangement of natural forms and how can we readily translate these rules into feasible design models?

2. Matter, Structure, and Form

Matter is everything.

The search for a fundamental building block that constitutes the physical world has captured philosophers and inventors alike. It would seem that the understanding of the physical world is an act of perception and a metaphor for the human mind striving to complement its own being. String theory is a prominent branch of theoretical physics that seeks to describe a mathematically complete model of the universe. It draws from quantum mechanics to postulate a theoretical explanation for the universe’s fundamental duality, which suggests that both matter and energy, attracts both space and particle properties. String theory argues that the material, forms, and forces of our reality by whether ordinary or mysterious, quantifiable or unquantifiable are entirely comprised of discrete one-dimensional units. The properties of these fundamental units or strings are given by equations involving superstrings and perturbation theory. Strings exist in different medleys. The frequency or vibrational mode of a string determines the physical characteristics, features and attributes it manifests. In string theory the strings become electron, proton, gluon, etc. Within the framework, matter is a self-sustaining quantum network of discrete energy-database, synthesized by “modifications, particle-bond, charge of force, or string and string, line and line.” (String Theory, 2005). An intermediate parameter is the proportion of the same fundamental building block differing only in levels of organization and order. Matter is defined and determined by energy for forces and action.

To describe the map in which strings, merge through space and time, string theory forms the most inherent forces of action. The calculations are fundamentally based on Lagrange metrical, which demonstrates that an obstacle subjected to thermal influences determine a future path that involves a certain quantity, its action. Naturally occurring structures exhibit adaptive mechanisms and an elastic elegance that can be attributed largely to the way strings are packet together and string. The bundle is subject to thermal properties, the situation of stress, and the amount of force to which it is subjected. For the moment, we consider that the term “form” is an inherent force of action. The adaptation of its inherent force to its environment makes it a part of the force energy-states operating conventionally as a fundamentally integrated system. Forces and actions are vital features of the emergent condition that shapes our universal conditions.

3.2 RESONANCE AND SOUND

An impressive visual example of the energetic ordering of a natural form is the fin of a fish, a Cyrtocara, which is the study of standing waves. Gilbert Galef first noted these phenomena in Dialogue Concerning the Two Chief World Systems. He observed when scratching a fish across a brass plate, a sound could be produced that created geometric order to a square in the water. By using his own fish, a major mode can be produced on a square set of metal plates when he has a wire cross a glass drum covered in fish. In a century later, Ernst Chladni repeated and expanded on Huygens’s experiments before publishing Chladni’s experiments in the Theory of Sound, in which he discusses a method for visualizing the various modes of vibration on a mechanical surface.

Chladni documents a way of visualizing the resonance of particular materials and Dr Chladni’s observations are significant because they define the physical properties of materials and their behavior. In essence, they are primary observations. He proposes a basic principle of resonance and the importance of order to create unique patterns corresponding to the form and its inherent resonance. Much like string theory allows the vibrational mode of a string determines its physical characteristics, the emergent pattern defined by resonance are not rigid, but conform to an elastic template that can be continually transformed by engaging various conditions. Resonance in a material system defines organic topology – structure – rather than topography – phonology.

The patterns in Figure 1 are a selection of still images from a video frame that are sourced in character or YouTube. They illustrate the phase changes of a material system being ordered by resonance. The arrangement is formed not with a fixed plate connected to a fixed generator. Sound produced by the tone generator resonates through the steel plate and introduces an energetic fluctuation into the material system in a fashion that – which responds initially by selforganizing toward local action. The wavefield within the material represents a form of waves and a form of energy that are the vibrational modes of a system toward a more evidently defined level of organization, suggesting that higher harmonic modes are directly linked to increased organizational complexity. An important observation is that coherent forms is a global trait of each phase. The self-organizing systems tend to exhibit the same kind of behavior regardless of the fluctuation of the closed energy-states operating conventionally as a fundamentally integrated system. Forces and actions are vital features of the emergent condition that shapes our universal conditions.
3 Energy Centre Design Principles

3.1 LOCAL CHANGE, GLOBAL CONSEQUENCES: THE DYNAMIC LANDSCAPE

The self-organization phenomena associated with dynamics are related to non-linear thermodynamic principles. The chaotic structures described by Nobel laureate Ilya Prigogine propose that thermodynamic systems in equilibrium are an exception rather than a rule. He argues that self-organizing matter operates in an open system of energy, not a closed system. Although the overall state is ordered, such that a slight local-energy fluctuation can be amplified to have substantial global effects (Prigogine, 1985), in contrast, a system in equilibrium requires large amounts of energy to change its state. The energy sensitive nature of dissipative structures means that self-organizing formations can quickly and efficiently adapt to changes in their environments.

In his essay, "Landscape of Change," Santford Akin eloquently discusses the metaphorical view of "creating by emergent, fuzzy and self-organizing forces" in systems and processes designed to be "good systems." He asks designers to engage with biology and philosophy. Akin’s ideas for the future of design systems and processes can be seen as an early step in a visual analogy to describe an inherently connected architectural design process that operates in a responsive and fundamentally adaptive manner. Designers are urged to engage processes that correspond to the flexible landscape of dynamic equilibrium in which a local change is "helped through out the system to affect, in turn, conditions all across the event surface." Where "global behavior is an emergent property unpredicted by local rules" (Prigogine, 1985), architects are challenged to consider their role in shaping environments in which human and only architectural equations, that is, as self-generated diagrams (Akin, 1992).

Akin makes a strong argument for a self-sustaining approach to design. However, the reader is left wondering how these concepts might manifest as practical architectural design processes. What kinds of design tools incorporate principles of self-generation, evolution, and equilibrium?

3.2 GENEBS DIVISION/REFORMATION

In 1995, John Frazier published an essay, "Evolutionary Architecture," proposing a bold new direction for urban development by redefining an emerging "architectural concept". Frazier’s argument is based on the idea of computing to model physical, material, and environmental characteristics. Through a simulated process of self-organization and evolution, architecture becomes "the expression of an equilibrium between the ongoing development of the architectural concept and the inevitable influences exerted by the environment." (Frazier, 1995). Evolutionary architecture is defined by a set of design rules, a
characteristic of naturally occurring self-optimising structures (Mattick 2008). Nature is a master of elegance and material efficiency. the value of Material's insight transcends the mechanical and is readily transferable to design and engineering.

In zone reviewers we are now seeing a greater awareness of corollary constraints (Barr 1992). Finite element analysis is used to identify the critical stress elements and the FEM apparatus aims to remove redundant elements, consequently altering the geometry toward a uniform stress, distributing material while maintaining stiffness of the structure. The original concept was extended to include the addition of materials to high stress regions and was easily adapted to bi-directional Evolutionary Structural Optimisation (ESO). A number of analogous tools have since been developed in research practices around the world. Chris Malthouse has implemented his own evolutionary algorithm for structural optimisation called SoftWitch (2007), philip more from ECE architecture and design research has developed an equivalent code for use with Mathematika, and Ole Samland et al maintain a series of compatible web-based tools, broadly named topology optimisation tools. Japanese structural engineer Taturo Satoh is another key proponent of this technique, having developed a similar methodology titled 'extended Evolutionary Structural Optimisation (ESO) to consistently design, its other innovation relevant to structural optimisation cases the principle of evolution and self-organisation of evolving structures, adopted from an engineering standpoint, to generate natural structural shapes within a computer (Satoh 2007). The inputs needed for a ESO model and basic parameters assembled from context analysis and design intent. These parameters can cause dramatic change in structural geometry, load cases, boundary conditions and design elements such as materials, styles and fastenings. The nature of finite element analysis is to fundamentally change the components to meet end user requirements or optimization criteria.

4.2 ESO AND THE ARCHITECT

The ESO algorithm primarily utilizes Abaqus CAF for modeling, visualization and the evaluation analysis. Although Abaqus includes a powerful parametric modeling environment, its deterministic interface is not suited to the generative methodology offered by ESO, particularly with respect to the exploratory stages of an architectural design. Furthermore, due to the restrictive interface ESO users and developers have been limited to working with simple solids. A minor example of this disciplinary knowledge transfer is a discovery by the author that enables geometry to be imported from non-regular and empty environments using a standard ESO file format. This means freedom is preliminary geometries can now be defined in less rigid environments such as Max, 3DSmax or Rhino. Before importing materials, loads and supports is advisable.

To integrate architectural design considerations within ESO, it is necessary to become familiar with the behaviour of the algorithm and how at least some level of four-physical structures are likely to act under force. As an architect, this takes time and experience. The emerging interaction of the ESO research science and simple continuous geometry to evolve into unimaginable variations depending on assigned materials, the placement of supports and the magnitude of loads. The radically different outcomes illustrated in figure 3 serve to demonstrate the concept of dynamic filtering optimisation for architectural design. and the significant consequences of a single parameter’s change. In this case, a new load added to the centre of the preliminary carcase form. completely restructures the outcome. Fundamentally, design becomes energy-centric, as form, function and structure mutually depend on the enclosing of energy states. A moment of transfiguration is shown through the structure and arrangement of the final form. The evolution is visual by abstracting design intent into a series of engineering parameters describing materiality, leading conditions and supports.

4.3 ADAPTING TO SOFTWITCH’S DESIGN

In a digitally based analysis environment, designing materials, determining scaling conditions and picking supports, reduces energy an efficient through an otherwise natural generative code that responds to external forces by self-organizing into optimal ‘trimetres’ forms. In contrast to designing a simple singular response, the architect defines an implicit generative system capable of producing infinty variations. The search space explores all the possibilities of the given conditions. The work of Fraser et al. at the Architectural Association is a precursor to an early one design approach. An Evolutionary architecture emphasizes the role that nature can play as a model for architecture and the importance of abstracting physical environmental form and material charctersistics into a digital language that can be used for architectural design. The particular notion of form that is discovered enables variable structural evolution of external forces by emulating nature’s efficient, energy driven design processes. By applying “form generation models that recognize the laws of physics and are able to invoke ‘minimum surfaces for compression and bending (and tension)” (Gross 2004), design becomes a dynamic process related to the morphogenetic activity of the field.

3.2 TRIM-DIRECTIONAL LOGIC

To engage with energy driven design processes, of critical importance is the ability to employ structural, environmental and material properties within a digital environment. So that do we envision fluctuation in otherwise rigid digital geometries. The answer lies within the tools of other disciplines such as engineering, for example common finite element analysis utilizes algorithms that compute physical quantities such as forces and internal properties. By engaging these tools and tools architects can enclose the variable space that is still physical yet in digital form.

This three disciplinary log emphasizes a cross-cultural approach to design and informed architecture from its visual perspective. (Gross 2004) has explained, “Like architects should consider (these) as we view the world, it is the abstract forms and the way they are constructed interact the world.” (Tumle 2004). We are at the precipice of a significant transference of the language of architecture with science and engineering vis-a-vis an abstracted vocabulary of energy transaction and mediation. the shift calls into question the traditional architectural-engineer relationship by replacing the traditional interaction of the 20th century with a renewed synergic collaboration that proliferates design outcomes with multidisciplinary aspects that previously existed in isolation.

4. Case Study

4.1 INTEGRATION TO BI-DIRECTIONAL EVOLUTIONARY STRUCTURAL OPTIMISATION

The Ascent of Urbanism (Drez) is a phrase coined by Professor Chris Malthouse, whose re-search into how growth has demonstrated that urban stress is a common structure
Evolutionary Plasticity involved a number of insights relevant to designing with optimisation tools. As the offering of scales of optimisation emerged, it became clear that there was an intrinsic link between performance and aesthetics. Does structural efficiency give way to functionality, or do the form or parametric frameworks necessarily intrude on design vision? How do the tendons toward periodic, perspect and figure structures, suggesting that multi-scale and multi-criteria optimization should be derived from the bottom up, instead of global form being the fine optimization procedure, a family of variable and physically response structural cells should be defined first. These could be aggregated at various scales according to physical and environmental constraints, forming an efficient, integrally and elegant macro structure. This intricate scale of consideration has an immediate and dramatic effect on the overall concept of architectural design or form generation.

6.2 STRANGE ATTRACTOR

Strange Attractor is a passion for wine tasting in Southeastern Victoria, Australia. It is a project undertaken with Muse Design Studio. The design strategy for the scheme is an oscillation between two distinct points. These points are the two primary attractors of the plan, the bar and the restaurant. To describe the energetic oscillations of gaits, the Lorenz attractor was chosen as a parametrical diagram to which to organize and evoke a spatial experience of distinct but internally connected spaces.

The challenge was to articulate this oscillating architecture and environment as a IMPOL woof. Firstly it was necessary to locate the attractors within a pre-existing geometry defined by the presence of the site and building. Numerous approaches were explored, including defining new design regions and concentrating supports and loads. The final strategy (Figure 7) involved the creation of a topological oscillating scheme, organized in a sense region and the inclusion of two voids to locate the attractors and create the desired eight figure oscillation of the plan. Considering the theme of the paper, the ontological conditions applied in the final BREEZE study can be regarded as forming the system's energy state with architectural stage steps.

The form that finally emerged from the many iterations of the co-creation and optimization process was a smooth structural spine defining the initial geometry into two distinct but internally connected spaces. The attractors, seen as void spaces, become integrated with the structural spine as archeons, which arrange to form continuous coverage spaces on the interior. A point for further research is that evolutionary optimization processes cannot produce finished buildings, but rather a preliminary aspirational process to set criteria. To transform this particular geometry into architecture, a secondary strategy was necessary to enclose the internal spaces while maintaining coherence of the elegant structural spine.

The solid topological form that emerges from the BREEZE process was analysed to determine sub-optimisation and fabrication strategies. The design team explored the role of a three-dimensional tracking system to increase material usage and increase the strength to weight ratio of the final structure. In order to negotiate fabrication considerations, the modelling of the digital model was significantly downsized to accommodate larger frame members (Figure 8). The reduction strategy allowed for initial selection criteria to be transformed to conserve grid size. The resulting proposal (Figure 9) was paired building envelope supported by triangulated framing that aesthetically mitigates the transition from surface to structural role.

6.3 structure resolution

The projects outlined above are an introduction to working with BREEZE as an architectural design tool. A series of further investigations are planned to expand on the insight gained thus far. The bottom-up cellular design methodology employed in Evolutionary Plasticity will be expanded further to provide a specifically tailored feature set of BREEZE. In addition, there is a significant potential to explore in the parameters of periodic structures. Another exploration will include the optimization of sculptural geometries that capture specific design intent and are visually generated in the form modeling stage. Further research is necessary in architecture.
To facilitate multi-criteria evolutionary optimization to dimensionally meet an optimal topological response combining design, structural and environmental criteria.

8 Conclusion
In this research energy consumption and emissions driven global environmental pressure to achieve more with less has had a profound impact on the direction of contemporary architectural thinking. Architects are searching for deeper resonances with the natural world and have turned to computation in an attempt to transcend the rational. Our research results a comprehensive understanding of the fundamental properties that organic matter as structure and form. This paper argues for an energy semi-morphological architectural design, which reflects the awareness that optimization of nature is complex, a generality of resilience and has the potential to leverage both the convergence of the design process and the outcomes produced.

The architectural approach for architecture proposed by John Pawson in 2004 is central to this discussion; however, where Pawson’s discussion primarily focuses on maps of generality, the generality of semi-morphological architecture emphasizes the empiricism of abolishing the formal world into a set of modeled energy based solutions that simulate physical and environmental conditions. The RESC case study presents the integration of an energy aware structural optimization logic. The initial materials, loads and supports assigned to the digital model operate to define particular energy scales throughout the preliminary geometry. This energy signature is a significant design component of this system. This forces that all to define an optimal topology – a path of least action. By reversing the path, RESC enables the design’s morphological and algorithmic data to be utilized both simultaneously andmultipartly to achieve a pre-established and optimally computed design.

The concept of inducing energy dissipations into otherwise inert digital geometry closely aligns the architectural design process with the principles of metabolism. Architecture enters a trans-disciplinary condition governed by energy driven crime and complexity becomes a tool with which to fuse biometric material systems toward optimal design performance and ultimately, construction.

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Introduction
Negotiating design and performance with engineering and fabrication has been one of the central topics of contemporary architectural discourse. Driving this discussion is a growing awareness of ecology and sustainability, as global warming, rising fuel prices and renewable practices become central concerns of an increasingly energy conscious society and resource driven economy. Searching for ways and means to minimize energy consumption and maximize material efficiency has revived interest in the synthesis of natural forms as a model for architectural design.

The beauty and complexity found in nature is exquisitely coherent, economical and adaptive. The natural world has provided inspiration for architects throughout history from the exuberantly ornate Corinthian columns of ancient Rome and the whimsical Art Nouveau style to the modern Organicists and post-modern Metabolists. Although many designers have been inspired by the novel functionalism and elegant coherence of the natural world, they have been somewhat limited to visual and metaphoric appropriation, unable to directly harness nature's sophisticated growth strategies and performative capabilities to enhance their design practice. Only recently, advancements in computation and software have enabled simulation of the complex, non-linear dynamical processes responsible for shaping the physical world (Frazer 1995). As the physical sciences delve ever deeper into the structure of matter and the quantities that govern the formation of natural systems, contemporary architectural design has an opportunity to transcend the metaphor by abstracting natural phenomena into design parameters that can be used to drive generative digital models. So we might ask, what governs the arrangement of matter as structure and form and how can we codify these rules into feasible design models?

Force and Form
The various forms and qualities of naturally occurring structures can be largely attributed to a universal phenomenon, described in the 1740's by French mathematician Pierre-Louis Maupertius as the principle of least action. Biologist D'Arcy Thompson also raised awareness of the integral connection between dynamic systems and exogenous forces stating, "The form of any particle of matter, whether it be living or dead, and the changes in form which are apparent in its movement and in its growth, may in all cases be described as due to the action of force" (Thompson 1917). Lagrangian mechanics, commonly used in quantum physics and advanced engineering, confirms Maupertius' principle and Thompson's observations by demonstrating that any object subjected to external force will follow a path that minimizes its action. In other words, "the evolution of any dynamic system will always follow the path of least work" (Alexander 2004). The word 'force' can be substituted with the term 'energy' so we may conclude that natural structures respond to contextual energy fluctuations by self-organizing toward the most efficient formation possible, their form of least action.
Spatial Information Architecture Laboratory (SIAL) and an engineer from the Innovative Structures Group (ISG) at RMIT. This trans-disciplinary alliance was formed through a mutual interest in adaptive, minimal energy and materially efficient structures.

Tensional Integrity and Material Efficiency

The concept of tensegrity is an incredibly flexible and widely adopted natural structural strategy relevant at many scales. It has been used to describe the configuration of the universe (Fuller 1979), the physiology of the human body (Levin 1980) and the structural behaviour exhibited by carbon atoms, water molecules, proteins, viruses and other biological cells (Ingber 1997). Tensegrity was first explicitly created by sculptor Kenneth Snelson in 1949 and later named by R. Buckminster Fuller. The term describes structures that are stabilised via tensional integrity. That is, they comprise of discontinuous compression members held together in a ‘sea’ of continuous tension.

The tectonic significance of tensegrity structures is their incredible adaptability and material efficiency, achieved by distributing and balancing forces through discreet axial loads of tension and compression. This fundamental structural characteristic drastically increases strength to weight ratio by strategically using tension members and eliminating the need for bulky compression elements that resist bending and torsion.

Physical Vs Digital

Tensegrity structures are notoriously challenging to physically build and digitally model. Moreover, due to complex interdependent structural relationships, their non-linear behaviour is exceptionally difficult to accurately analyse without the use of a computer. This incongruence presents a problem when attempting to explore the suitability of tensegrity structures for contemporary architectural applications, particularly if one intends on deploying complex or novel configurations. An initial complication is the inability of standard 3D modelling software to adequately simulate the complex systems found in the natural world.

Self-organisation and Digital Form Finding

Nature’s self-organisation phenomena are the result of energy transactions that are best described by non-equilibrium thermodynamics and the theory of dissipative structures proposed by Nobel Laureate Ilya Prigogine. Prigogine suggests that thermodynamic systems in true equilibrium are an exception rather than a rule and argues that self-organising matter operates in an open relationship of energy exchange with its context such that it maintains a steady state far from equilibrium. In contrast to a system in equilibrium requiring large amounts of energy to change its state, self-organising formations can quickly and efficiently adapt to subtle energetic fluctuations.

Our recent ability to digitally simulate the complex systems found in the natural world is an open invitation to explore the architectural potential of inducing energetic fluctuations into otherwise inert digital geometry. By deploying digital “form generation models that recognize the laws of physics and are able to create ‘minimum’ surfaces for compression, bending [and] tension” (Cook 2004), architectural design can become a dynamic form finding process infused with the precarious sensitivity of life itself. Stunning architecture can emerge as a steady state far from equilibrium; order on the edge of chaos.

This significant shift in design thinking aligns the language of architecture with science and engineering via an abstracted vocabulary of energy transaction and modulation. It necessitates trans-disciplinary dialogue from the outset of design and calls into question traditional architect-engineer relationships by replacing the distanced interaction of the past century with a renewed synergetic collaboration that proliferates design outcomes neither profession could develop in isolation.

Tensegrity

The following observations detail the first stage of an ongoing collaboration between a PhD candidate from the Spatial Information Architecture Laboratory (SIAL) and an engineer from the Innovative Structures Group (ISG) at RMIT. This trans-disciplinary alliance was formed through a mutual interest in adaptive, minimal energy and materially efficient structures.

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software to account for the physical forces necessary to induce a state of tensional integrity. In attempting to understand the nature and behaviour of tensegrity structures within a digital framework, it becomes necessary to look beyond standard 3D modelling environments to software that supports physics-based parameters.

Preliminary exploration used 3DS Max for its ability to realistically simulate the action of cables (springs) and struts. The embedded physics engine was exploited to encourage self-organisation by inducing an energetic potential in simple inert geometry. Rigging a mutually dependent system of prestressed springs and struts made it possible to digitally form find tensegrity arrangements. This simple mechanism ensured that models could be physically realised and enabled a vast range of complex configurations to be digitally explored.

Throughout this investigation it has become apparent when dealing with complex structures that it is vital to integrate both physical and digital models into the design process. The physical enables proof of structural concept and basic characteristics to be concretely defined, while the digital enables these characteristics to be encoded and explored with increased precision and speculative abandon. Designing tensegrity structures therefore demands constant feedback between the digital and physical, where each paradigm informs the following iteration of the other in an ever-rising spiral of refinement. Herein lies fruitful territory for exploring the nexus between the digital and physical, the technological and phenomenological, the quantitative and qualitative.

The Authoring Hand(s)

Tensegrity structures are exceptionally minimal and are traditionally built to accentuate their elegant efficiency. While it is possible to optimise structure toward fundamental vectors of tension and compression, this makes it less than ideal for use in architecture and leaves little room for the designer. The models presented in this exhibition are just one step beyond the purely analytic sculptures of Kenneth Snelson et al. They speculate about the architectural potentials of contemporary tensegrity structures.

The fundamental tensegrity principles ascertained through synergetic collaboration between architect and engineer has enabled a range of tensegrity modules to be developed. These have focused on limiting degrees of freedom to increase suitability for architectural applications. The process up to this point has incorporated numerous physical models explored from both an engineering and design standpoint. The final modules selected are based on stable polyhedra for their combination of mechanical properties and variability. After digitally generating the precise platonic geometries of tetrahedron, octahedron and icosahedron, their aesthetic and architectural possibilities were explored. Prior familiarity with fine feature modelling at the scale of jewellery enabled the speedy generation of a range of bespoke modules. These were easily converted into fabrication information for 3d printer and laser cutter.
The outcomes from this investigation are truly trans-disciplinary. The engineering knowledge required to understand tensile structures coupled with design expertise and digital fabrication know-how has meant that architect and engineer have mutually benefited from the integrated collaborative process to produce models that neither could have generated in isolation.

Final Note

New digital processes infuse a certain liveliness into the process of architectural design, however they do not give conclusive and final solutions to architectural problems. Pure optimisation is not the answer but simply provides a suggested composition over which any good design team should be able to paint their masterpiece. The authoring hands guide the diagram toward a steady state far from equilibrium where it reveals an optimal configuration solution for a given set of design, engineering and fabrication criteria. Interpreting the diagram as a rational object engages the personal sensibility and prior experience of the authors.
TENSYREITY 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 seeking to exploit lightweight and rapidly deployable structural solutions for mass production or temporary construction. This is of particular interest to a variety of researchers, the ability to determine, control, visualize and deploy tensegrity structures within buildings, construction or extensile cladding. This paper presents a novel approach to tensegrity through the development and methodological analysis of 3D ‘compressed’ components. A range of rheological models is presented to illustrate some of the configurations and arrangements that have been assembled by the authors. Comprehensive 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 approach is a significant step towards computational platforms where design and engineering information can converge. That is, digital modeling environments where form is intricately linked with force and design conception is cohered with appropriate strategies for design realization.

Keywords: Tensegrity, 3D Compressed Components, Force Finding

1. INTRODUCTION

1.1 Tensegrity

The notion of tensegrity is relevant to many structural systems. One example is 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 solids (Ingber 1997). Although initially conceived as a novel approach to structure for the purpose of an invention in 1969, research into tensegrity and its applications in architecture and engineering has been growing steadily. Two important contributors, Richard Buckminster Fuller and Kenneth Snelson are regarded as the pioneers of tensegrity – a contraction of the words tense and integrity, coined by Fuller in his patent document. He described a tensegrity structural system as “an assemblage of tension and compression components arranged in a discontinuous suspension system.” (Fuller 1962). Snelson submitted his own patent titled “Continuous tension, discontinuous compression structures” (Snelson 1963) and has referred to tensegrity as the “floating compression principle” (Snelson 1966). The more comprehensive definition and 3D extensions that specifically covers the novel structures described in this paper is presented by Renc Moto.

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 (Moto 2002). Tensegrity structures are mechanically stabilized through the interaction of discrete systems of discontinuous compression and continuous tension. By distributing structural forces through discrete paths, tensegrity networks eliminate the need for rigid 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 leads to reconfigurable forms and shape-shifting structures with variable rigidity “in which all parts exist in a dynamic equilibrium” (Hannay 1992).

1.2 3D Compressed Components

Tensegrity is of interest in architecture and engineering because it enables the exploration of lightweight, high-stress 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 compression, fabrication complexity, inadequate design tools and poor load response (Buhlman 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 (Figures 1(a)), which is formed using planar X-shape elements and cables. A further example is Snelson and Fuller’s original ‘tensegrity man’, 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-convoluted cable-net systems” (Wang and Li 2001). 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 Kagome and 3D tetrahedral tensegrity structure. Figure 1(a) is the classic X-Piece created by Snelson in 1949 and Figure 1(c) depicts a tetrahedral membrane 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 solver 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. Adapting 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, Moto 2002), a stable, self-equilibrated system created through discontinuum.
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:

- Extenuate vertices bound a volume
- 3D components connect to the tension network at exterior 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 refining spores from the gravitational centers of each polyhedron to its respective vertices. The 3D components generated through this investigation were fabricated using both 2D 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 tessellate 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 ensures a more refined level of design control.

Table 1. Assembly of 3D components

<table>
<thead>
<tr>
<th>Modules</th>
<th>Required pieces</th>
</tr>
</thead>
<tbody>
<tr>
<td>i. Tetrahedron</td>
<td>2 x tetrahedral angle</td>
</tr>
<tr>
<td>ii. Octahedron</td>
<td>Linear bar, X-piece</td>
</tr>
<tr>
<td>iii. Rectangular Prism</td>
<td>2 x X-piece</td>
</tr>
<tr>
<td>iv. Elip Prism</td>
<td>Linear bar, tetrahedral angle</td>
</tr>
<tr>
<td>v. Cuboctahedron</td>
<td>2 x X-piece, 2 x tetrahedral angle</td>
</tr>
</tbody>
</table>

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

Figure 3. 3D components assembled using 2D laser cut pieces
Following are basic examples of initial design investigations conducted 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.

2.1 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. Tetrahedral module and component

We have explored this component in several examples. A seven level tensegrity tower was created in 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 exactly 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 rigidly 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 tetrahedron tube shown in Figure 7 illustrates this potential. The tube is connected with self-stress 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 cuboctahedral 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 cuboctahedral 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 – tetrahedron tube
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 tensile integrity. This characteristic enables shaped texturing on a variety of structural elements. One team has approached this additional potential in a number of ways and we have subsequently developed a general procedure for designing tensile structures with 3D compressed components.

- Define a 3D component and tensile 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 Tensile 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 alternative 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 lower cut and 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 element

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 tension forces into the element that must be absorbed by rigid joints at each vertex of the final 3D component. These joints must receive 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 component. At a scale models the structure was observed to maintain self-stress. Some of these investigations are illustrated in figure 10.

5.1.2 Using Computational Form Finding to Expand the Design Spectrum

We have discussed that once a series of tensile module components 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 tensile structures in a digital environment is no easy task and requires form-finding procedures that can establish "true geometry compatible with a soft-stress state" (Nito 2002). Unfortunately, this functionality is generally not supported within the current generation of off-the-shelf CAE and CAAD software (Burkhardt 2007, Steck 2007).

In order to explore a variety of forms for the footbridge structure without painstakingly raising numerous numeric towers, a unique ziva approach 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 incorporating tension and compressive forces. Struck calculates the form of a system given its initial geometry and the desired end 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 structure 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 tensile structures is presented in an upcoming publication by the authors (Fremar and Zure).
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 Snaek. Shortening the rest length of the cables along one or two edges distorts the structure from a semicircular tube into a sharply arched form as shown in Figure 13. 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 Fosforbridge (Figure 14).

The wire frame model generated in Strack was exported to Rhinoceros and fabrication considerations were taken into account. 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 15 shows them to be satisfactorily similar to conclude that Strack is a useful tool for finding the form of tensile structures with 3D compressed components. It is clear from the digital and physical models that the bridge conforms to the definition of tensile structure.

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 universe or 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 introduced previously. The authors developed this proposal as an entry to the 2009 Evolo skycraper 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" (Bleuworths 2009). This response from the architectural community demonstrates the nascent potential of tensile 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.

The component was further developed to enhance its functionality and suitability to the project goals. A flange 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 off-site. The structure
would be ejected on-site by sequentially pre-
stimulating the horizontal tensile bands. When a
horizontal band is fully pre-stressed, the con-
crete components are structurally activated.
The hinge enables the compressive assembly to
pivot from planar into a V-shaped position and
lock 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 14.

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 dem-
strated that given that such a structural system
will yield a wide variety of interesting architectural forms and spatial conditions. The commercial benefi-
cits of a rapidly deployed deployer of high-rise
is obvious. Once the final high-rise strategy
was proven to be functional, the Struck
apparel 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 18: Computational form finding to explore
alternate high-rise form

5. CONCLUSION

The work presented here is the result of a col-
aporative process between architects and
engineers. It demonstrates a co-ordinated 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 by the use of 3D compressed components.

This paper proposes a novel technique for
constructing a variety of 3D components from 2D prints. 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 geometries
demonstrates that a series of stable forms can be generated from a single structural
design. 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 apparel 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
conception is emeshed 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 (Fruma and Perou
2009). Specifically these publications deal with
the computational form finding and explorations into the use of 3D compressed components in
tensegrity assemblies. It is important to note,
more work is necessary in the field of mathematics and engineering before these
structures can be fully integrated into design and
construction processes.

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Motro: specifically covers the novel structures described in this paper is presented by Rene compression system.” (Fuller 1962). A more comprehensive definition and one that assemblage of tension and compression components arranged in a discontinuous joint pioneers. In his patent, Fuller describes a tensegrity structure as “an many contributors, Richard Buckminster Fuller and Kenneth Snelson are regarded as tensegrity and its applications in architecture and engineering has a long history and conceived as a novel approach to structures for the purpose of art, research into molecules, proteins, viruses and other biological cells (Ingber 1997). Initially 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). Initially conceived as a novel approach to structures for the purpose of art, 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 joint pioneers. In his patent, Fuller describes a tensegrity structure as “an 1D strut, 2D X-shape and 3D tetrahedral tensegrity ‘masts’

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).
Practical Examples of 3D Components and Structures

Constructing 3D Components From 2D Pieces

To test the notion 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. Principally, components were developed by radiating spokes from the gravitational centre of each prism to their respective vertices. For practical and economic reasons, three basic laser cut pieces were developed to enable quick and easy assembly. Some of the 3D components that can be created with these pieces are shown in Figure 2. It should be noted that the authors have carried out extensive morphological investigations, only a few of which are presented in this paper.

Figure 2: Assortment of 3D components assembled using laser cut planar pieces

Tetrahedron

The tetrahedral component is the most basic, and easily assembled for practical purposes using 2 tetrahedral angles connected perpendicular to each other and rotated 90 degrees. A seven level tensegrity mast was created as an initial investigation and is pictured in Figure 3. In this case the vertical cables in the tower structure were manually adjusted to achieve a slight curve in two directions. The tetrahelix tube also illustrated in Figure 3 illustrates another possible configuration.

Figure 3: Tetrahedral component, seven level tensegrity mast and tetrahelix tube

Cuboctahedron

An outcome of the initial phase was the generation of a number of unexpected elements. One example is the cuboctahedral component (pictured on far right of Figure 2). This geometry proved useful for the design of a variable tensegrity frame system. A tensegrity node was developed that allows the frame to expand in six directions (Figure 4). The node is formed using a cuboctahedron and four tetrahedron modules. It is infinitely extensible in X and Y axes using tetrahedron modules and in the Z-axis using rectangular prism modules.

Figure 4: Cuboctahedral component, tensegrity node and frame assembly

Tools For Designing Tensegrity Structures

Physical vs Digital

The assemblies presented thus far are basic examples that demonstrate the feasibility of tensegrity structures with 3D compressed components and hint at their architectural potential. Although limited, these physical investigations have been invaluable for enhancing the authors understanding of how tensegrity structures work and creating a bi-directional feedback loop between design and engineering teams. Through these explorations, it was quickly determined that a number of different forms can be explored for any given tensegrity structure by adjusting the lengths of tension members. Testing this in reality proves challenging. While basic structures composed of 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 suggests that a dynamic and ideally interactive digital model is necessary to support the early stage design exploration of tensegrity structures. A computational tool of this nature is significant as it provides a platform for the convergence of design and engineering information; an environment where form is synonymous with force.

Existing Computational Approaches

Because tensegrity structures are mechanically stabilized through the action of pre-stress, they do not require anchorages points or external forces to maintain a static equilibrium. This results in statically indeterminate structures that cannot be adequately described by the current generation of CAE and CAAD software (Burkhart 2008, Sterk 2007). To determine the shape of tensegrity assemblies, form finding procedures are necessary to “find a geometry compatible with a self-stress state” (Motto 2002). As mentioned earlier, engineers, mathematicians and programmers have driven much of the research and discourse around tensegrity structures and this includes research into computational methods of form finding. The methods and algorithms that have been developed thus far by Motto, Tibet and Pellegrino, Skelton and others have not yet been fully integrated into design environments. Needless to say, there are exceptionally limited tools available to designers wishing to explore the potential of tensegrity structures in the virtual paradigm. Presently those that exist can be grouped into three broad categories: