Ossature:
Bone Remodeling as a Generative Structuring Process in Architecture

by

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Abstract

There is an inherent and complex interrelationship between material, structure and form that exists in nature, whereby each informs the other through a dynamic process. In nature, form is not imposed; instead it emerges as an expression and articulation of dynamic material responses to environmental stresses and circumstances. I propose looking at this responsive form generation as a model for developing architectural structures.

Specifically, this thesis proposes looking at bone tissue remodeling as a new generative process for structure in architecture. Bone tissue becomes highly optimized by the self-organizing and remodeling of its structure in response to loads; creating a complex structure that is both high in strength and low in weight. Its shape is directly informed by the forces acting upon and within it; material and structure are distributed along stress paths three dimensionally.

The objective of this research will be to examine the feasibility of utilizing bone remodeling algorithms as a generative design tool in the development of structures in architecture.

Definitions

Algorithm – A sequence or procedure for calculation

Additive Manufacturing (AM) – The process of making a three-dimensional object by successively adding layers of material

Anisotropy – The property of being directionally dependent

Bidirectional Evolutionary Structural Optimization (BESO) – Based on FEM, iteratively adds or removes material from a structure

Computer-Aided Optimization (CAO) – Based on FEM, this method thickens highly stress areas of a structure much like a tree

Computer Aided Internal Optimization (CAIO) – Based on FEM, optimizes fiber orientation within an object

Evolutionary Structural Optimization (ESO) – Based on FEM, iteratively removes unused material from a structure

Finite Element Analysis (FEA) – The application of FEM to solve engineering problems

Finite Element Method (FEM) – An analysis technique used to solve a complex equation using many smaller equations

Generative – Refers to a rule based system where complex behaviours emerge from the interaction of simpler elements

Isotropy – Identical properties in all directions

Load – a force applied to a structure causing stress, deformation or displacement

Optimization – In engineering, refers to the selection of the best solution from a set for the condition of maximizing or minimizing a desired property

Soft Kill Option (SKO) – Based on FEM, removes under-stressed material within a design boundary

Strain – A measure of deformation representing displacement relative to a reference length

Stress – In engineering, refers to the measurable quantity of internal forces of an object

Topology – The study of surfaces, concerned with preserving spatial properties under deformation

Topology Optimization – A mathematical approach that optimizes material layout within a design space for a given set of loads so that the result meets desired performance targets

Von Mises Stress – A criterion used to predict yielding of materials under any loading condition

Voronoi – A way of dividing space into regions where a set of points has a corresponding region consisting of all points closer to it than to any other

Young's Modulus – A measure of the stiffness of an elastic material defined by the ratio of stress along an axis over strain

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1 Chapter: Preface

1.1 Introduction

This is written with the anticipation that biologically inspired structures will become increasingly common in architectural practice. Biologically inspired architecture employs concepts and notions, like development, growth, adaptation, and morphogenesis, which already have counterparts in nature. A better understanding of these biological processes can inform architectural design because design often aims to resolve problems that have already been resolved by nature. Can this translation of these processes into the built environment be more than simply a superficial use of biological concepts and could this affect our relationship with our natural environment?

1.2 Objectives

The research from this thesis will be developed into a biologically inspired computational approach for architectural form generation. This inspiration is derived from the unique properties of bone and their potential application in generating architectural structures. The tools and software needed to model these properties will be investigated. Further research will look at the work of biologically inspired contemporary architects and researchers like Achim Menges, Michael Weinstock, Neri Oxman, as well as the preceding works of D'Arcy Thompson, Antoni Gaudí, and Frei Otto.

From this research a methodology will be developed that simulates the remodeling of bone and investigates its possible applications and implications in architectural design. Structural prototypes and experiments will be produced to demonstrate the scalability and range of applications. Digital simulation, prototyping, material studies and scale model building will be key tools in this investigation.

The design work will culminate in several prototype structures which exemplify the qualities and strengths of the bone remodeling algorithm as a structural generator. The development of these structures will also be examined with regards to existing and future manufacturing technologies, such as 3D printing and large scale additive manufacturing, as well as the potential material solutions required for the construction of such structures.

2 Chapter: Nature as Inspiration

> "The most expert Artists among the ancients…were of Opinion that an Edifice was like an Animal, so that in the Formation of it we ought to imitate Nature." - Leon Battista Alberti, *On the Art of Building in Ten Books*, *Book IX, Chapter V*

2.1 Biomimetics

Although Buckminster Fuller is often credited with some of its earliest incarnations, the concept and term biomimetic was coined by engineer Otto Schmitt in the 1950s while creating a device that could replicate nerve propagation. But it is Janine Benyus, a natural sciences writer, who is responsible for popularizing biomimicry as a discipline. Her book *Biomimicry: Innovation Inspired by Nature* compiled discoveries from an array of disciplines whose research investigates the designs and processes found in nature. She proposed that humans should emulate and take inspiration from nature as model for our own problem solving as 3.8 million years of evolution has provided us with highly refined processes and organisms.

Biomimicry is the imitation of natural forms and systems that are proven to be optimized and efficient. The overlaying of the biological model on architecture can potentially lead to new insights and innovations. Transferring these models into architecture is desirable because natural models have come into being through the process of evolution, adapted and subjected to many diverse conditions. The appeal of biomimetics stems from a desire to acquire resonant abstract design ideas from nature and also from the manner through which nature utilizes those ideas. It stems from our human desire to imitate. They represent extremely complex solutions and their translation is not simply a matter of form.

Previously, biomimetics in architecture has taken inspiration from late 19th century biology through the works of Ernst Haeckel and the publication of D'arcy Wentworth Thompson's seminal book *On Growth and Form* published in 1917.

2.2 Mimesis

To better understand the implications of biomimicry we should examine the etymology of the word. *Bios* is the Greek word for life. *Mimesis* is a more complex word; it roughly translates to imitation, but the Greek concept of mimesis is more than simply imitation. Mimesis has its origins the Greek arts, a key principal of the arts was the use of imitation, mimesis, as a means of creating a correspondence between the real world and the created world of the arts. It is a way for humans to participate in the order of the universe. Mimesis is not only the means of production it is also the intended product (Aristotle, 11).

Aristotle believed that imitation is natural to humans, it is how we learn and we enjoy recognizing the original in the imitation. It is the natural mode of constructing and inhabiting the world. For Aristotle the idealized imitations are what hold value and the value of imitation is in the production. The object of imitation is an ideal and can exceed its representation. Imitation is not simply a derivative action, but one that entails understanding.

In the 17th and 18th Centuries there is a turn away from the Aristotelian concept of mimesis as an abstraction or idealization of nature and a move towards realism in the arts depicting things as precisely as they appear.

In the 20th century, Hans-Georg Gadamer a German continental philosopher, in his writings on art and aesthetics also takes on the notion of mimesis. For Gadamer mimetic action is reversed, something is not waiting to be copied it comes into being through imitation. Imitation is production. It allows the subject of imitation to become more fully itself. Imitation gives us the ability to see the unseen. As Gadamer puts it, "What imitation reveals is the real essence of the thing." (Gadamer and Bernasconi, 99). An idealization can yield insight into phenomena precisely because it is selective. It is the exemplification not the resemblance that is crucial in imitation. It gives us access to features that are otherwise difficult to discern.

> "By omitting or downplaying the significance of confounding factors, they constitute a cognitive environment where certain aspects of their subjects stand out. They thereby facilitate recognition of those aspects and appreciation of their significance. They thus give us reason to take those aspects seriously elsewhere." (Frigg, et al., 2010, 15)

Problems arise when art seeks to mirror nature. A precise replica is not the goal and effective representation should embody and convey an understanding of the subject. Imitation entails nothing about the appearance of this encoded information. In terms of biomimetic architecture, a building that is inspired by a tree does not need to resemble a tree in order to maintain the original essence.

> "Mimetic ambition has stood as a crucial point of conjunction between science and visual art. As the artistic ability to draw empowered Leonardo da Vinci or Galileo to perceive scientific features of natural entities which remained completely unintelligible to their contemporaries." (Frigg, et al., 2010, 3)

This emphasizes that there is validity in the architectural imitation (in its truest sense: mimesis) of nature. Architecture through imitation has the capacity to bring to light new characteristics that remain obscured.

2.3 Analogy

Of all the sciences, it seems to be biology that architects most often turn to for analogy. Architect and writer Philip Steadman, in *Evolution of Design*, outlines several types of analogies: The ecological analogy, the suitability of a building for its environment; the organic analogy, the relationship of parts to the whole; the anatomical analogy, relationship between body and building. The biggest issue with drawing comparisons between architecture and biology is that buildings are not living organisms like plants and animals, but are traditionally mostly static. To be truly biological the materials need to have the ability to self-analyze, repair, and break down. Indeed, the most convincing similarity between architecture and biology is the influence of environment on design.

2.3.1 The Anatomical Analogy

Of greatest interest to this thesis is the anatomical analogy. It is obvious how much our architectural language uses anatomical metaphors, such as: 'skin' and 'skeleton', the 'head' and 'foot' of a column, and the 'wings' of building.

The most basic example of this anatomical analogy in architecture takes the form of a comparison of the skeleton with the structural framework of a building (columns and beams). This comparison of structure with skeleton is epitomized in Gothic cathedrals. They were built, to an extent, to imitate the structure of bodies; the tall, delicate columns and ribbing could be compared to the bones and the thin stone exterior to the skin.

French cathedrals of the 12th and 13th centuries, express this flow of forces; their appearance and beauty results from an economy of structure. Eugene Emmanuel Viollet-le-Duc wrote extensively about these underlying structural principles in Gothic architecture. He saw the pattern of ribbing of the vaults and the buttressing as the expression of the most structurally economical distribution of forces.

> "Weight was pared down to an irreducible minimum, and opposing structural forces were exactly reconciled in the ingenious systems of counterbalanced vaulting, piers and buttresses which the Gothic builders had evolved."(Steadman, 40)

Gothic buildings increased the span the enclosed volume, while at the same time reducing the size of supporting walls to a bare minimum. The exterior walls were continually optimized; unnecessary and underutilized material was removed and replaced by large areas of glass filling the space between external buttresses. So optimized was the design that even the seemingly decorative features of Gothic architecture had structural function; mouldings and masonry pinnacles were used to provide counter-weight to resist lateral forces (Steadman, 41).

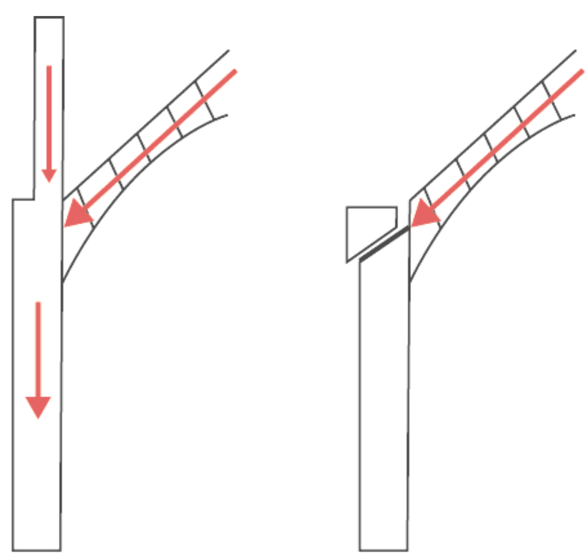

Illustration 1 Pinnacle prevents sliding failure due to lateral forces exerted on a buttressing pier

The added weight of the pinnacle to the pier prevents failure by directing the lateral force downwards through the pier and into the ground.

It seems that structures designed and or constructed using biological principles even if they do not mimic every specific feature can still function as successful analogues.

2.4 Models

To better understand the how we can achieve mimesis through architecture we turn to a discussion of models. Models are symbolic representations used to create a correspondence to reality, so it may be fruitful to examine the idea of models with mimesis in mind.

Philosopher Max Black describes two types of models: scale models and analogue models. Scale models, as one might imagine, are proportional representations. Analogue models are those which reproduce faithfully the original in a new medium while retaining the original structure of relationships.

> "The analogue model shares with its original not a set of features or an identical proportionality of magnitudes but, more abstractly, the same structure or pattern of relationships." (Black, 223)

The analogue model is most closely related to the act mimesis; they retain the original essence regardless of form. Models enable us to see things that may be otherwise be overlooked, to shift our emphasis and to see new connections. They can provide a common ground for understanding and inference. Models allow for mimesis.

> "It follows that some features of the model are irrelevant or unimportant, while others are pertinent and essential, to the representation in question. There is no such thing as a perfectly faithful model; only by being unfaithful in some respect can a model represent its original." (Black, 220)

This sentiment echoes Aristotle and Gadamer: the point of using models is not to create exact replicas, but instead to emphasize certain aspects in order to better understand them.

3 Chapter: Form and Formation

"Nature delights in transformations." –Isaac Newton[1]

3.1 Morphogenesis

For clarity I will briefly describe the concept of Morphogenesis. It is a term broadly meaning the formation of shape and structure by a coordinated growth process and or mechanism. The word is derived from the Greek terms 'morphe' (shape or form) and 'genesis' (creation). It originated as a branch of biology in the early 1800s that focused on the variation of biological forms.

3.1.1 Goethe

Johann Wolfgang von Goethe introduced morphology in his 1790 work *The Metamorphosis of Plants*. In plants he saw a model for the continuous metamorphosis and plasticity of form that permeates living things; he did not embrace a deterministic view of growth within an organism. Instead, for Goethe, nature grows through continual conflict, both external and internal. With his concept of morphology he broke with the contemporary models of nature which treated life as an inanimate mechanism. In it he established that gestalt (form) was inseparable from bildung (formation); morphology is about the processes of umbildung (transformation) that governs the form rather than the form itself.

In plants, all parts excluding the roots, are modifications of the leaf: from the seed on to the cotyledons, leaves, petals, and flowers. Although all plants differ from each other they are all variations of a fundamental generative plant, which he called Urpflanze.

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[1] Note: In this case Newton is speaking of physical transformation rather than evolutionary

The Urpflanze is essentially a pattern of development that is present in every plant from which the plant's formation can be derived. Every part of the plant is a stage in the continuous transformation of the leaf (Goethe).

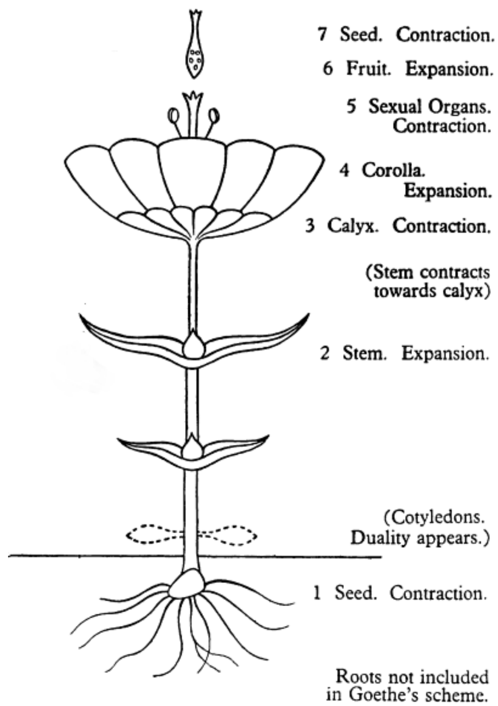

Illustration 2 Goethe's Urpflanze and its seven stages (Ronald Gray, *Goethe the Alchemist*, p82)

With his theory of the development of plants Goethe laid the foundation for the geometric relationship of form and formation integrated as part of a system.

3.1.2 D'Arcy Thompson

The mathematical comprehension of this relationship between form and formation was established in the work of Scottish naturalist and mathematician D'Arcy Thompson. In his 1917 book *On Growth and Form* he defined the underlying math and physics that describe form and its formation specifically through the causative influence of physical forces on form.

> "We rise from the conception of form to an understanding of the forces that gave rise to it; and in the representation of form and in the comparison of

> kindred forms, we see in the one case a diagram of forces in equilibrium, and in the other case we discern the magnitude and the direction of the forces which have sufficed to convert the one form into the other." (Thompson, 270)

Form is the organization of matter subject to physical principles such as surface tension, gravity, and pressure. It is the patterns of energy, more so than material, that give shape to an object. Any form must be examined not as a solitary object but rather as an entity embedded within its environment.

Like Goethe, Thompson's morphology lies in comparing related forms rather than defining them precisely. The process of comparison is done through geometrical transformations using a Cartesian coordinate grid system that provides a basis for comparative geometric relationships and transformations. From this grid he is able to translate any form into series of *x*, *y* coordinates.

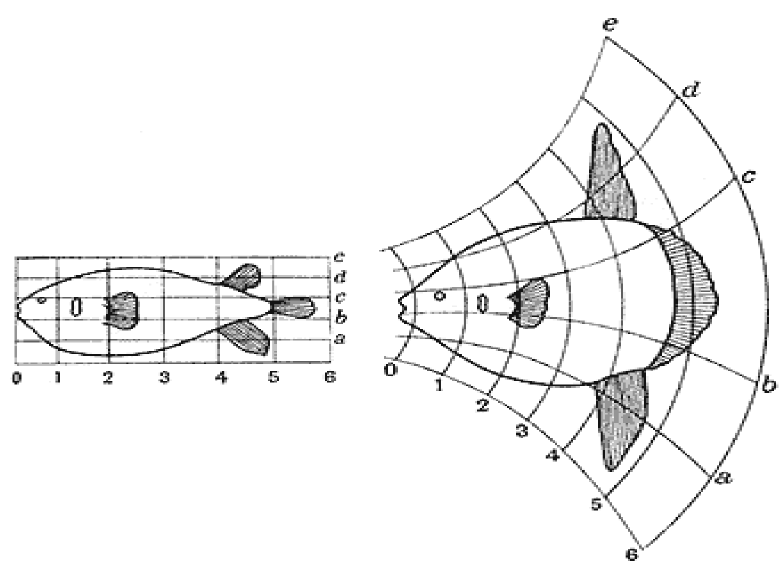

Illustration 3 Thompson's morphological process relating forms of fish through transformations (Thompson, 301)

After altering or deforming the grid the resulting form can then be plotted from its original coordinates (shown above); every form is a transformation of another. From this newly deformed grid it is possible to extrapolate the magnitude and direction of forces involved in the transformation. These forces can be seen as analogous to the environmental forces that may have led to the transformation of one organism into another. The relationship of the original coordinate system to the transformed one provides possible clues to the forces and rules that govern of growth. Thompson's transformative technique visually elucidates that form is relational and situational.

Thompson's comprehensive catalog of forms and their fundamental mathematics have been a great source of inspiration to architects with the rediscovery of his book. Thompson's diagrammatic morphological models and their variations can be more easily adapted and manipulated using modern analytical tools for architectural design.

3.2 Digital Morphogenesis

The appropriation of morphogenesis in architecture characterizes an approach to design using digital media as a tool for the generative derivation and transformation of form, aspiring to express processes within the built form. It is design established through a set of rules for a formation process generated by internal and external forces.

Digital morphogenesis in architecture is related to the processes of morphogenesis in nature, sharing a dependence on gradual development but not necessarily adopting the actual mechanisms of growth or adaptation. A literal importation of biological structures or processes into architectural design is usually not feasible, meaningful or desirable. But the principal logic of these processes may be valuable in the design of architectural structures (as discussed in Chapter 2).

The use of formative and generative processes in architectural design is not a new phenomenon. Rule based generative design processes have been used in the works of

Frank Lloyd Wright and Le Corbusier in the development of their architecture. While Wright is concerned with the connection of building to nature neither system is biological in the same way that digital morphogenesis is, however both set a precedent for rule-based architecture.

In the 1926, Le Corbusier formalized a system of design, his *Five Points for a New Architecture*:

1 – Pilotis: to support and elevate the building
2 – Free plan: absence of supporting walls
3 – Free façade: the exterior is separate from the structure
4 – Horizontal windows: better illumination and views
5 – Roof gardens: replace the green space below with one on the flat roof

These generative rules were developed out of advances in construction techniques at the time, notably reinforced concrete. In his built work the five points are most explicit in the design of Villa Savoye.

In Frank Lloyd Wright's work it is the prairie houses that exemplify the use of a generative processes.

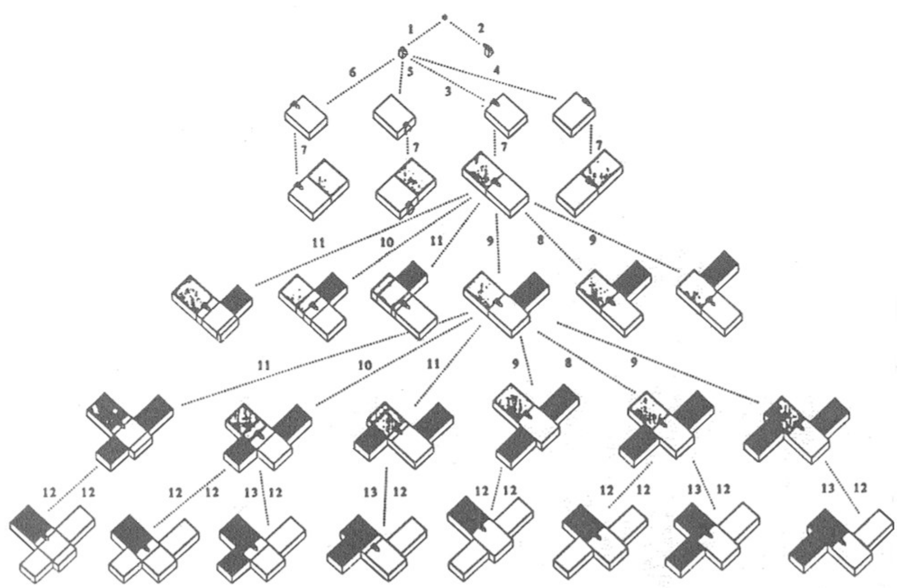

Illustration 4 A design tree showing the evolution of the prairie house originating from the fireplace (Koning and Eizenberg, 305)

The design is centered on the fireplace around which blocks, distinguished by program and function, are oriented and overlapped orthogonally to form the basic composition for the house. The social areas (living and dining room) are added first followed by service spaces (kitchen) and private spaces (bedrooms) in an additive process (Koning and Eizenberg).

The processes of generative design adopted by Le Corbusier and Wright are still fundamentally form oriented design. However, digital morphogenesis generates architecture in a radically different way; it is about form-finding rather than form making. Architect Neil Leach is his essay *Digital Morphogenesis* describes it as:

> "…design that seeks to challenge the hegemony of top-down processes of form-making, and replace it with a bottom-up logic of form-finding. The emphasis is therefore on material performance over appearance, and on processes over representation." (Leach, 34)

Often in the use of these processes architects act more as facilitators of the generative processes rather than strictly as designers, however it could be argued that the influence of the architect's design intent acts as an additional force that informs the generative process.

Architect Achim Menges is both a proponent and critic of digital morphogenesis. For Menges, digital morphogenesis risks becoming a cliché in architectural design and he advocates moving beyond simple digital shape-making. His major criticism is that we develop processes to generate shapes which do not integrate any material or construction logic. And likewise, ignore the performance of a form in terms of efficacy of material, structure, and energy use. Ultimately, concerned only about appearances and not fulfilling the real promise of morphogenesis in architecture (Menges, 2008).

In contrast, real digital morphogenesis will arise from the system's generative logic and as a response to environmental relationships and programmatic constraints; it must take in to account the performative qualities of form.

> "The existing object always embodies both process and result. The integrity of form, structure and function in nature makes purely morphological translations worthless." (Gruber, 15)

Morphogenetic design has the capability to deal with pressing architectural issues if we can move beyond shallow biological formalism and instead apply the integrated logic revealed in nature's design by keeping in mind the true meaning of mimesis.

4 Chapter: Bio-logical Design

> "Human subtlety…will never devise an invention more beautiful, more simple or more direct than does nature, because in her inventions nothing is lacking, and nothing is superfluous." - The Notebooks of Leonardo da Vinci

4.1 Nature's Design Rules

Nature utilizes a variety of processes and methods of formation to ensure a maximization of structural efficiency and mobility all the while minimizing material use. Examining the logic of biological design can give us insights into the development of efficient structural and material organization. The following sections are some of the fundamental 'rules' in the development of a natural form.

4.1.1 Minimum Energy

The creation of any type of structure requires the use of energy to produce and maintain the materials that make up that structure. In nature, these energy requirements can mean the difference between life and death. By reducing the amount of material used in its structure a biological entity can gain an advantage in survivability by being lighter and faster than another entity. To reduce material, structures will grow to distribute stresses proportionately and evenly. This strategy of optimization creates a distribution of material only where needed, resulting in a high strength-to-weight ratio. Natural forms and structures develop such that they use minimum energy in response to environmental forces and loads (Thompson).

Additionally, in order to conserve energy organisms must maintain an efficient balance between their surface area and internal volume. Certain forms, like a sphere, are able to maximize the internal volume while minimizing surface area. A smaller surface area reduces the heat loss and requires less materials to form the organism while reducing the weight (Tsui, 1999). These methods of resource conservation to establish minimum potential energy are universal and can be found at all scales of development.

4.1.2 Axiom of Constant Stress

In nature only the most efficient designs survive and in order to do so they must be lightweight and optimally resistant to loads. Under-loaded areas waste resources and overloaded areas create structural failure; the ideal balance has neither under or overloaded areas, creating a uniform distribution of maximum stress throughout. The mechanical rule that determines this design is known as the constant stress axiom, whereby a biological entity subjected to a load will grow to be in a state of constant stress (Baumgartner, Harzheim, Mattheck, 1992, 387). Stress and strain become the basis for structure. This is a universal rule for the design of structures in nature and is most explicit in the structure of bones and plants.

4.1.3 Optimization

In nature the process of optimization takes place by non-optimal solutions being eliminated, leading to remaining load carriers being optimally adapted. Mattheck and Tesari suggest that this adaptation can be achieved either by trial and error or self-repair by adaptive growth, as with bones and trees. The second adaptive method allows the optimal design to change under new loading conditions.

Adaptive growth is the process by which trees and bones achieve a uniform stress distribution across their surface. Trees can only add material to overstressed areas while bones are able to also remove material in under-stressed areas. Bone can grow and shrink as a means of controlling loads and this ability to keep weight at a minimum is a useful design strategy for the survival of mobile animals (Mattheck and Tesari).

With natural objects competing for space and energy, only the designs most resilient and efficient with respect to energy and material use can endure. It is this condition of lightweight yet resistant that can be found in nearly all biological load carriers.

Mattheck suggests when looking at nature for inspiration it is best to copy the method of optimization rather than the design of the object because the design emerges from the optimization in response to particular loading conditions. This is particularly sage advice when dealing with biomimetic design in architecture.

4.2 Form and Materialization

> "No material is without form and no form exists without materialization"
> (Kotnick and Weinstock, 106)

4.2.1 The Significance of Form

The preservation of form is important for the continuation of function in nature. All objects are subject to gravitational forces, with other forces deriving from the shape and function of its form as well as environmental conditions. The minimum requirement for the survival of an object is to withstand these forces; it is through the structure of its form that an object can fulfill its function.

Simply put, a natural structure's purpose it to support its own weight and that of additional forces, this process is called 'bearing'. This process is not the action of receiving the forces but the internal transmission of them. An object cannot bear a load without transferring and releasing it. The structure must be able to receive the load, transfer the load, and discharge it. Its function is the flow of forces and it represent its structural economy (Engel, 25).

When we treat material as separate from form, as occurs in form-finding experiments or structural analysis, the focus gets placed instead on the flow of forces. But the structural and functional are often indistinguishable in biological objects. Forces must flow through material and its arrangement influences the direction of this flow.

Material placement, particularly the proportional variation of it, in biological objects is what produces the ability to resist dynamic loads. This is most evident in wood and bone which redistribute material to adapt to loads. The relation between form and material is complementary; material behavior generates form (Kotnik and Weinstock, 2012). Material properties as input in generative design offers the possibility of creating more accurate constructions when we can anticipate the material behavior, when subjected to loads.

4.2.2 Material Organization

Biological systems use only a small range of materials but organize them very effectively for a variety of functions. A constraint in materials leads to a diversity in solutions. Most of these materials come in the form of fibre composites, of which there are four types: cellulose, collagen, chitin, and silk (Jeronimidis). These fibre composites make up structures that can be flexible like those of blood vessels and tendons or rigid like bones.

> "Biology makes use of remarkably few materials, and nearly all loads are carried by fibrous composites. They are successful not so much because of what they are but because of the way in which they are put together. The geometrical and hierarchical organization of the fibre architecture is significant." (Jeronimidis, 2004, 92)

Fibre composites are strong and because they grow adaptively under stress they can be arranged selectively in response to the direction of applied loads. To re-iterate, this geometrical organization and assembly, the anisotropy, is critical to the structural capacity that is generated.

4.2.3 Anisotropy and Directional Dependence

Anisotropy is the directional dependency of a material and is expressed as the difference in a material's physical property when measured along different axes. In biological materials it is typically linked to the microstructure, like the arrangement of fibres in wood for example, but can also be found in the global structure. Some materials like glass and metal are non-directional, isotropic, unless a secondary material is added to manipulate the orientation of the material.

The mechanical properties of a material, like strength and stiffness, depend on the orientation of its structure so when measuring wood's physical properties they will vary if measured along the grain or against it.

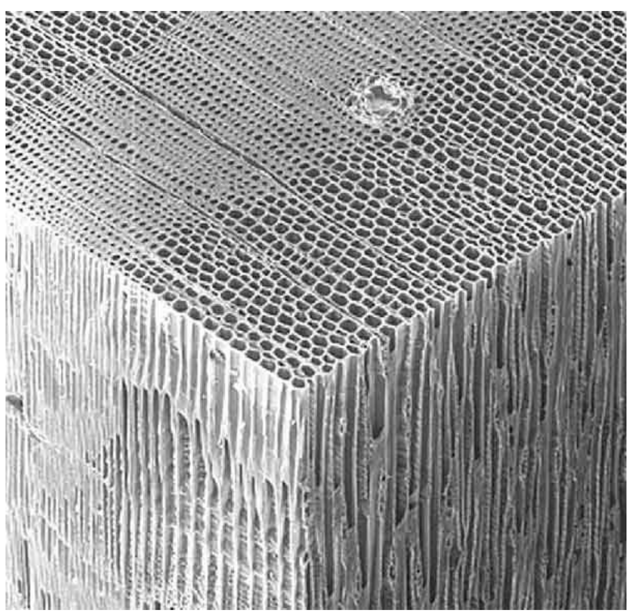

Illustration 5 A magnified view of spruce clearly showing the regular fibre orientation (woodmagic.vt.edu)

The Young's modulus[2] of the material varies with the direction and magnitude of forces. The Young's modulus will be higher when loaded parallel to the fibres since the fibre orientation provides paths in materials to transmit physical stress through a structure by creating continuous paths for loads. The directionality of a material is a response to environmental factors and aids in creating a more efficient structure by modulating the material locally for directional forces (Gibson and Ashby, 1997).

Cancellous bone tissue also has this property of anisotropy. Bone tissue has a homogenous material composition throughout the different regions of the body, but it achieves its anisotropy by the arrangement of the irregular lattice that creates the interior structure of the bone. Those lattices are references to the forces acting on them; the trabecular structure is shaped and oriented in the direction of the force imposed on it in order to maximize stiffness and strength. This arrangement is less a structure and more an example of material distribution driven by anisotropy (Oxman, 155).

The design implication is that by controlling and varying the microstructural arrangement of a material we can optimize the structure in terms of its weight and strength distribution. The use of anisotropy has been exploited in high-performance textiles with glass fibres and carbon fibres. The strength of a fibre is greatest along its length and so a composite material gets its strength by purposefully using this directionality. By organizing the weave you can maximize the density of fibres in a given direction and create the desired directional flexibility or rigidity, wholly or locally, within the composite (McQuaid and Beesley 2005).

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[2] Young's modulus (E) is the measure of the stiffness of an elastic material. It is the ratio of stress to strain along an axis

4.3 Form and Forces

> "The form, then, of any portion of matter, whether it be living or dead, and the changes of form which are apparent in its movements and in its growth, may in all cases be described as due to the action of force. In short, the form of an object is a 'diagram of forces'." (Thompson, 11)

4.3.1 Flow of Forces

The flow of forces through a structure is related directly to geometric relationships regardless of the material type. The path taken by the forces is always the shortest or most efficient one. However, in buildings this is not often the case; the structure if often developed subsequent to the form and potentially contrary to the natural flow of forces. Natural forms are ideal and 'optimized' models for structural development and as such cannot always be adopted literally, but they present us with the potential for developing resolutions to the separation of systems, for example: structure, enclosure and systems (Engel, 27).

4.3.2 Graphic Statics

The relationship between structural form and force was established with the development of graphic statics by German engineer Karl Culmann in 1865. His method was based on graphically representing the forces, both magnitude and direction, in a structure. The graphic method creates direct correspondence between the forces and the geometry of the structure itself.

This technique can be seen in Swiss engineer Robert Maillart's Salginatobel Bridge, a three-hinged concrete arch built in 1930. By using graphic statics the dimensions of the structure are pared down to a minimum and material use is maximized.

The depth of the arch varies with the compressive forces and its thickness increases at the center at its largest bending moment (Allen and Zalewski).

Illustration 6 Salginatobel Bridge near Schiers, Switzerland (Wikimedia Commons)

The Salginatobel Bridge is a clear expression of a form optimized by the flow and magnitude of forces through a material, in this case concrete.

4.3.3 Material Computation

The expression of the relationship between material and the flow of forces can be considered a kind of material computation; the materials self-organize under stress into stable arrangements. The form-finding experimentations of Gaudi and Otto precisely illustrate this. Their experiments with hanging chain catenary models, soap films, and wool threads are sophisticated analogues for determining structural function.

4.3.3.1 Catenary

A basic example of adopting natural force flows through a material system is a catenary (also known as funicular) structural system. A suspended cable subjected to an external load creates a catenary form that is dependent on the magnitude and position of the force. When inverted this becomes the ideal form for an arch that is subject to the same but opposing load. The flow of the tension in the hanging cable becomes the flow of compressive force when inverted. The form of the arch corresponds exactly with the flow of forces (Engel, 58). This process simultaneously determines structure and formation.

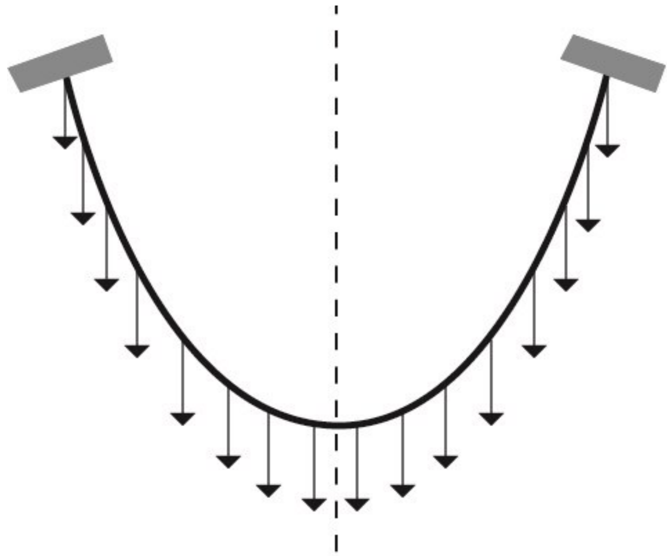

Illustration 7 Catenary curve from an evenly loaded cable

The discovery of the catenary is credited to Robert Hooke. The catenary was employed in the rebuilding of the dome of St Paul’s Cathedral in London after the Great Fire in 1666. Hooke’s law for the creation of a catenary arch was published posthumously and is as follows: "As hangs a flexible cable so, inverted, stand the touching pieces of an arch." (Jardine, 296)

Catenary curves were of particular interest to Antoni Gaudí, and Frei Otto after him because of the property discovered by Hooke that catenaries, when inverted, give optimal forms for vaults and domes. They require the least weight to support the given load and since the load is evenly distributed it is able to stand without buttressing. The size and scale difference between an experimental model and a building does not alter the shape of the catenary and because of this Otto and Gaudí were able to use scale models extensively. We must note, however, that the forces involved do not scale proportionally.

Illustration 8 Left: Gaudi's hanging chain model of Colònia Güell's church (wiki.ead.pucv.cl)

Illustration 9 Right: The catenary arches of Casa Mila's attic (Wikimedia Commons)

Shown above is a hanging chain model for the Colònia Güell church which uses a multiplicity of catenaries. This same technique was used to design the complex form of the Sagrada Familia. By following the form of the catenary Gaudí was able to develop lightweight brick masonry structures, as shown above in the attic space of Casa Mila.

4.3.3.2 Soap Films and Minimal Surfaces

Frei Otto is famous for developing analogue physical models that demonstrate force-generated forms based on material properties. He endeavored to solve structural problems using a minimal amount of energy. His experimentation with soap bubbles and films was used to develop models for lightweight roof and membrane structures by taking advantage of their peculiar physical properties

A soap bubble encloses a volume that is in equilibrium where the greater pressure inside the bubble is balanced by the surface tension as the soap attempts to minimize its surface area. The sphere of the soap bubble is its minimal surface. In contrast, a soap film is not distorted by air pressure because it is equal on both sides of the film but still creates a minimal surface. Given fixed boundaries soap will spread between them using the smallest possible surface area (Ball, 60).

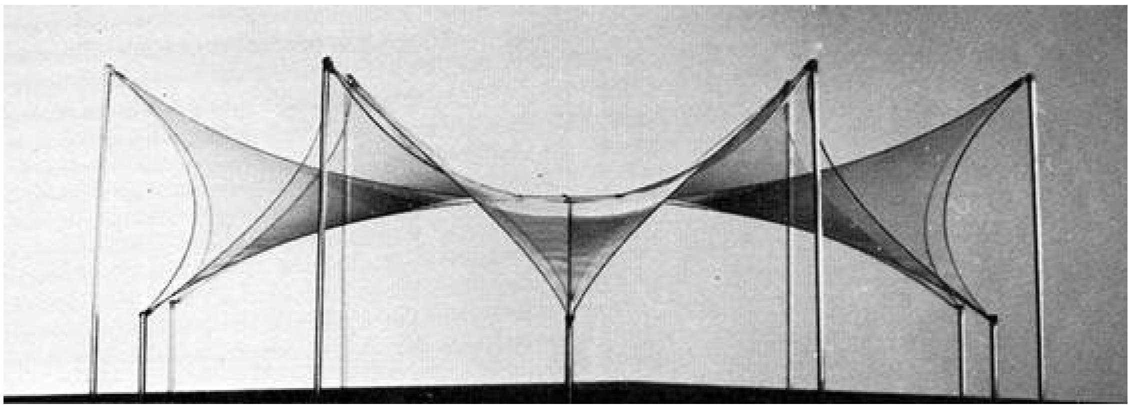

Illustration 10 Soap film model for a tent structure in Tanzbrunnen, Cologne (www.sl-rasch.de)

Using these properties of soap films Otto would dip a wire framework in soap to model the surfaces without need for a calculation; the solution is ‘computed’ by forces acting on the material. The resulting form is the most efficient one given the amount of material volume covered.

4.3.3.3 Wool Threads and Path Networks

In another of his experiments Otto developed a modeling technique as a means of reimagining circulation paths in a city. He began with a wool-thread model consisting of a frame with the threads attached in a direct path network (shortest distance) symbolizing a typical city grid. The threads are loosened to give approximately 8% additional length then the apparatus is dipped in soapy water. The surface tension of the water creates a branching-path structure with an optimized overall path, in direction not length, which reduces the number and length of paths (Frei and Rasch).

Illustration 11 Digital simulation of Otto's wool thread experiment

Structurally, the shortening of paths acts to reduce bending moments and the reduced material area creates a more energy efficient structure. This apparatus allows movement to be interpreted structurally by the material; it has just enough solidity to register changes and just enough plasticity to enable these changes.

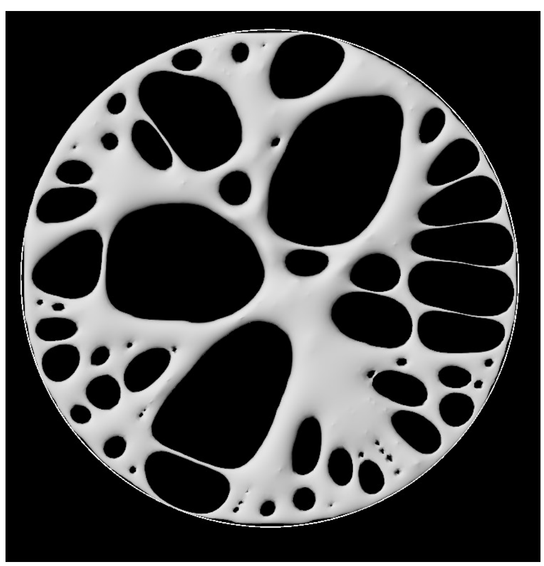

Illustration 12 A thickened mesh using the resulting wool thread paths. Note the non-coincidental similarity in appearance to bone.

This technique was also used three-dimensionally to model branching column systems and structures resembling cancellous bone. Both are all similarly anisotropic systems that economize on the number and direction of paths through orientation of fibers.

Form-finding design systems, like catenary curves, soap films, and wool threads are able to resolve the relationship between material and physical forces simultaneously by reaching a state of equilibrium.

5 Chapter: Bone

"If bone is the answer, then what is the question?" - Rik Huiskes, Professor of Biomedical Engineering at Eindhoven University of Technology

5.1 The Structure of Bone

Ostensibly, bones appear to be quite solid, the outer shell is composed of dense compact (or cortical) bone, but this outer appearance is misleading. The interior is a porous cellular filling known as cancellous or trabecular bone. The architecture of bone is dynamic and reflects a balance between the rates of its construction and deconstruction.

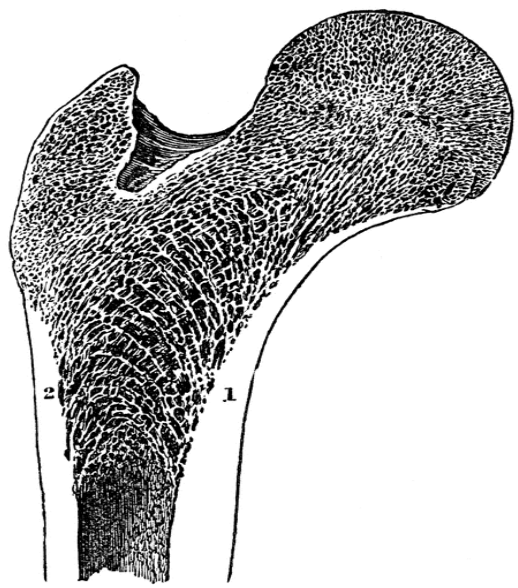

Illustration 13 Cross section of a femur showing the outer compact bone and interior cancellous bone (Calvin Cutter, *First Book on Analytic Anatomy*)

At the smallest scale, mammalian bone is a stiff composite material made principally of the fibrous protein, collagen type I, that is impregnated and mineralized with hydroxyapatite, a crystal of calcium phosphate. The other main constituent of bone is water which affects the overall mechanical behavior. The water and collagen comprise the bone matrix into which the mineral crystals are deposited (Currey).

The collagen protein molecule is synthesized into tropocollagen, which lines up and aggregates to form microfibrils, these microfibrils then aggregate to form fibrils. The tropocollagen molecules alongside each other are staggered by about one-fourth of their length. This leaves a gap, known as the hole region, between the head and tail of the molecules where the hydroxyapatite is deposited. These plate-like minerals then fuse sideways and lengthways, covering the collagen fibrils, forming larger lumps.

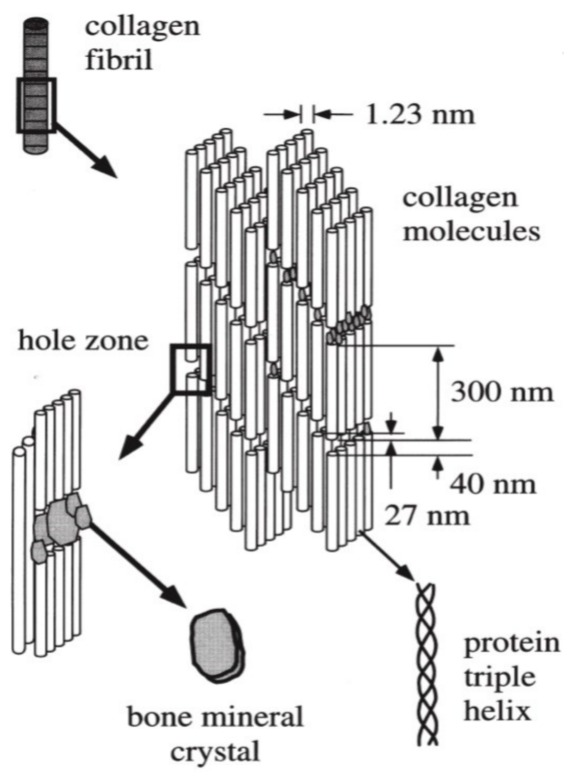

Illustration 14 Diagram illustrating the arrangement of fibrils and deposit of bone mineral (Currey)

At the next scale up bone is separated into two forms: Woven or Lamellar bone. Woven bone is an immature and quick forming bone tissue, found in fetal bones and in fractured bones, it has a haphazard organization of fibers and serves as a temporary structure until it is replaced by lamellar bone.

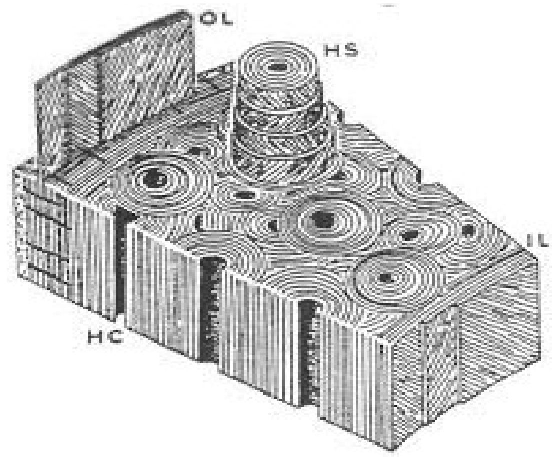

Illustration 15 Arrangement of lamellar bone into osteons. Note the alternating arrangement of fibres (Martin and Burr, *Skeletal Tissue Mechanics*)

Lamellar bone is more precisely arranged with the collagen fibrils and hydroxyapatite arranged in sheets, known as lamellae, which often appear to alternate in thickness. The fibrils lie parallel within the plane of the lamella and are arranged in alternating layers like plywood. The differing arrangement of these lamellae forms the osseous tissue, known as osteons, to be used in either compact or cancellous bone (Currey).

5.2 Cancellous Bone

Cancellous bone is rarely found on the surface of bones; it nearly always has at least a thin covering of compact (cortical) bone outside it. It occurs predominantly in four places: at the ends of long bones, through the length of short bones, such as the wrist bones, in large flat bones such as the scapula, and ilium, and where muscles attach to bones. The function of cancellous bone is not just to reduce weight but mainly to distribute loads from the compact bone over a greater area.

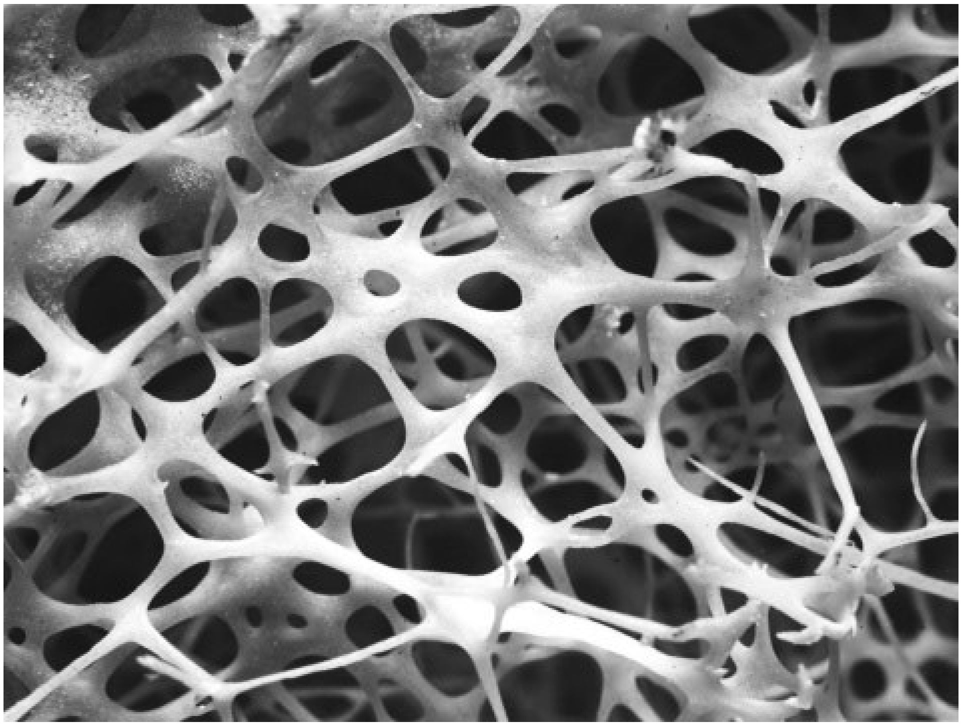

Illustration 16 A Scanning Electron Micrograph showing the porous cellular structure of cancellous bone tissue (Getty Images)

Structurally, cancellous bone is cellular in nature, the cells are composed of a network of rods, 200 μm thick, which flatten and fuse into plates as the density increases. The density of the network of cancellous bone is proportional to the magnitude of stresses it receives. The lowest density, rod-like structures develop where stresses are low and the higher density plate structures occur in areas of high stress. This structure of cancellous bone will change over time as the bone mass decreases with age and osteoporosis (Currey).

5.3 Mechanical Properties of Bone

Because bones are rarely loaded vertically, but more so as cantilevers, they are likely to bend under the downward load of the body's weight. When subjected to a bending load most of the load is carried by the bone's outermost layers. Material in the center now contributes little to bearing the load, but adds weight. So, for any structure that has to carry bending loads it is best to have material on the outside and minimize mass by reducing the material near the axis of the bending load (Turner, 72).

The mechanical behavior of cancellous bone is similar to cellular materials, like an open-cell foam, as the modulus of elasticity[3] and strength all depend greatly on the density of the cells. The stress-strain curve[4] is typical of cellular solids, which because of the slenderness of the connecting trabeculae fail by bending and buckling, especially at low densities. At higher densities the trabeculae instead fail by progressive microfracture. The Young's modulus (stiffness) and overall strength increase with density as well as with favourable trabecular orientation (Gibson and Ashby). It should be noted that the precise mechanical properties of cancellous bone are difficult to analyze because it functions as both material and structure and is always bound up within cortical bone.

The main adaptive feature of bone is its stiffness, as well as its strength. Bones would be stiffer if they were thicker, but this would increase their weight, size, energy requirements and so on, which would be less energy efficient. So nature has devised an optimization; the bone material will increase in volume and density becoming stiffer and stronger until a point where the increased in mass is more detrimental than the increase in stiffness. However, because bones have a much higher compressive strength than tensile they require the muscles to relieve tensile loading.

5.3.1 Bone Remodeling - Wolff's Law

Bone remodeling is the adaptive response to variations in environmental stresses, so if the stresses on the bone increase it will remodel itself in order to resist these stresses; the

[3] The stiffness of an elastic material. It is the ratio of stress to strain

[4] This is the deformation (strain) of a material relative to compressive or tensile loading (stress)

inverse is also true. This principle was established by surgeon Julius Wolff in 1892 when he observed the trabecular orientation corresponding to stress paths within the bone.

> "As a consequence of primary shape variations and continuous loading, or even due to loading alone, bone changes its inner architecture according to mathematical rules and, as a secondary effect and governed by the same mathematical rules, also changes its shape." (Wolff, 150)

This process of re-orientation and adaptation of bone tissue is known as Wolff's Law.

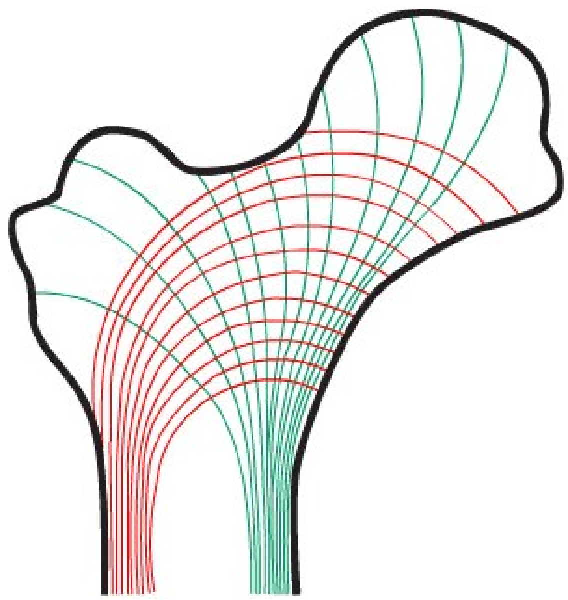

Illustration 17 Schematic drawing of a femur showing the principle stress trajectories in trabecular orientation.

Remodeling is triggered by mechanotransduction where a loaded fluid flows away from areas of high compression in the bone matrix signaling bone-building osteocytes. Bone design is a battle between Osteocytes and Osteoclasts to remodel the bone in response to loads. Osteocytes take calcium from the blood and use it to mineralize areas of bone. Osteoclasts on the other hand remove calcium phosphate and return it the blood so that it may be reused. This remodeling occurs until every area of the bone is subject to an equal amount of stress. Bone design ensures that both structure and function are optimized though homeostasis (Turner, 2012, 33).

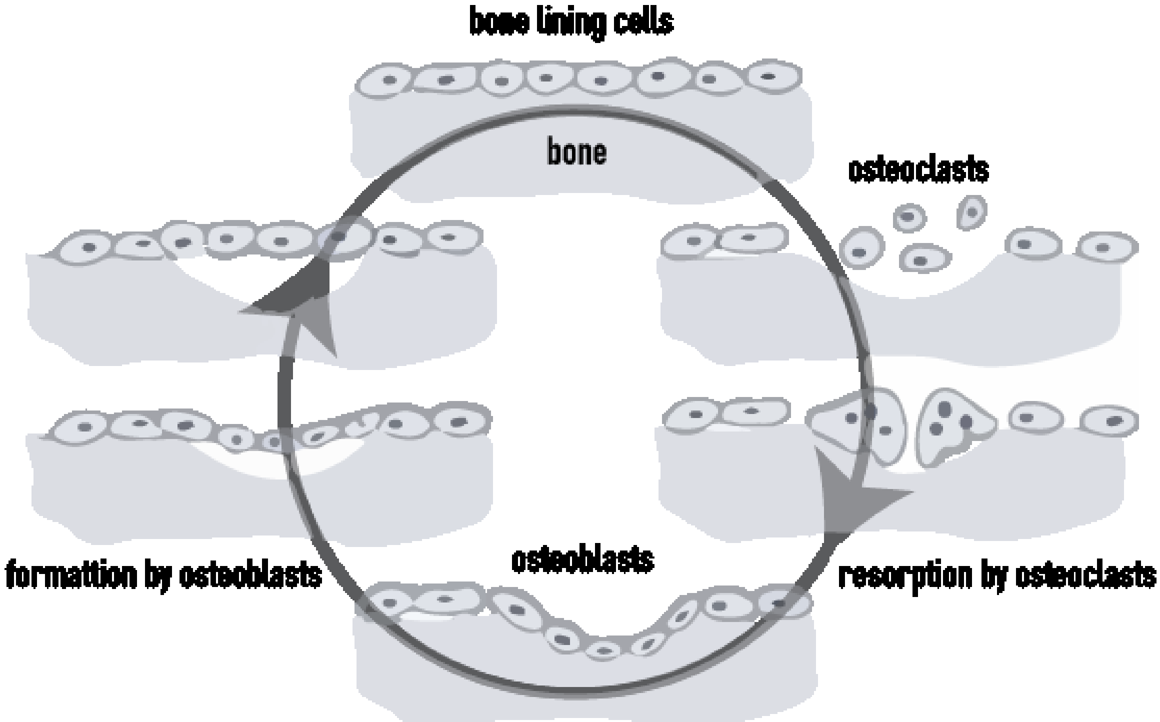

Illustration 18 The cycle of bone remodeling

This back and forth is carried out by three types of cells. One type, osteoblasts, constructs the bone by depositing calcium phosphate (hydroxyapatite) into the gaps of collagen. The second, osteocytes are mature osteoblasts which have become bone cells. The third, osteoclasts, dissolve the bone material laid down previously by osteoblasts (Turner, 75).

6 Chapter: Manufacturing Form

6.1 Material and Tectonic Analogues

Having examined the peculiar qualities of bone, how can we model forms that take advantage of its complex, strong and yet lightweight structure? The following sections will begin with an overview of cellular materials and review several methods of replicating bone structure and bone adaptability.

6.1.1 Cellular Materials

Cellular materials, also known as cellular solids, are assemblies of cells with solid faces packed in a way that they fill a space. These cellular structures are found in many disparate objects like bone, sponge, and soap foams. They all have a common internal structure of void cells with solid faces which pack into all available space with their density changing dependent on localized requirements.

Cellular materials have complex, self-organized structures which are redundant, high-strength, and permeable; consequently they offer interesting possibilities for architectural structures. The self-organization of these structure is a dynamic process that occurs over time by surface tension and competitive cell growth within a finite space; giving the system the ability to selectively modify itself while growing.

The distribution of cellular material typically falls into two categories: radial gradient and sandwich. Both arrangements combine fully dense material with cellular material to maximize performance for a given mass. The radial gradient structure is found in plant stems and is used to increase stiffness while reducing weight and buckling.

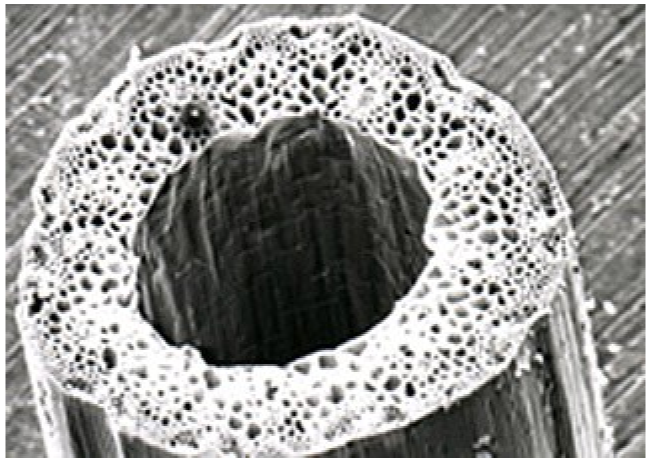
Illustration 19 Radial gradient distribution in a plant stem (Prof. Lorna Gibson, ocw.mit.edu)

The sandwich structure type places the stiffer material to the outside filling the remaining interior with a lightweight cellular core; increasing strength while reducing weight. Bone is a sandwich type cellular solid, it is essentially a mineralized foam with an intricate and anisotropic structure (Gibson, Ashby and Harley, 2010).

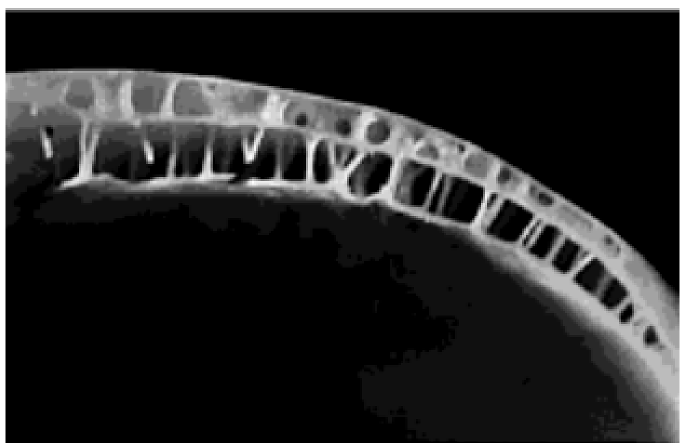
Illustration 20 Sandwich structure of a magpie skull

Man-made cellular materials are not as sophisticated as biological ones because we do not yet have the ability to constantly modify the internal structure based on performance requirements. However, man-made cellular materials are very light, durable, thermally resistant, and have high compressive strength. Additionally, due to the internal arrangement of the material they can have a high tensile strength.

The man-made structures come in two varieties: honeycomb or foam. Honeycombs are extruded or laminated sheet-like materials made of parallel prismatic cells. Foams have their cellular faces oriented randomly in three-dimensions and come in open or closed cell varieties depending on the manufacturing process used.

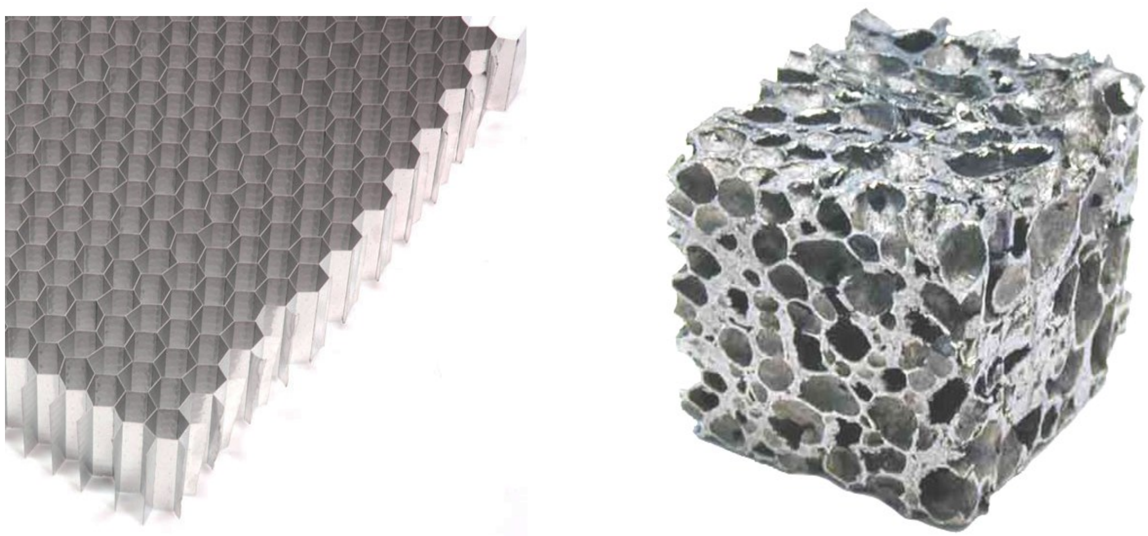

Illustration 21 An extruded aluminum honeycomb and aluminum foam (easycomposites.co.uk)

The process of foaming materials, typically bubbling an inert gas into a heated polymer, actually improves material properties when compared to a solid of the same material. Foaming can reduce thermal conductivity, improve the stiffness to density ratio, and increase kinetic energy absorption (Gibson and Ashby, 1997, 7). However, these man-made foams lack the cellular anisotropy that is present in natural cellular solids like wood or bone.

6.1.1.1 Case Study: Casting

This investigation into cellular solids was inspired by the work of D’Arcy Thompson as well as Frei Otto’s examinations into the geometry of cellular bodies. The cellular bodies, in this case water filled balloons, were allowed to self-organize into packed clusters within another outer form. The negative space around the cells was cast with plaster as a way to replicate cellular solids, or solid foams, with the casting process. Like cellular solids the anisotropy of the cells can be controlled by suspending, squeezing or pulling the form before casting. By applying force the fluid in the balloons flows away from the loaded areas resulting in an increased density in the negative space around the balloons near the location of the force. This increases the plaster density where it is needed most and reduces material in underloaded areas. This is much like the mechanotransduction that occurs in bone tissue which signals bone growth by the flow of fluids away from compressed areas.

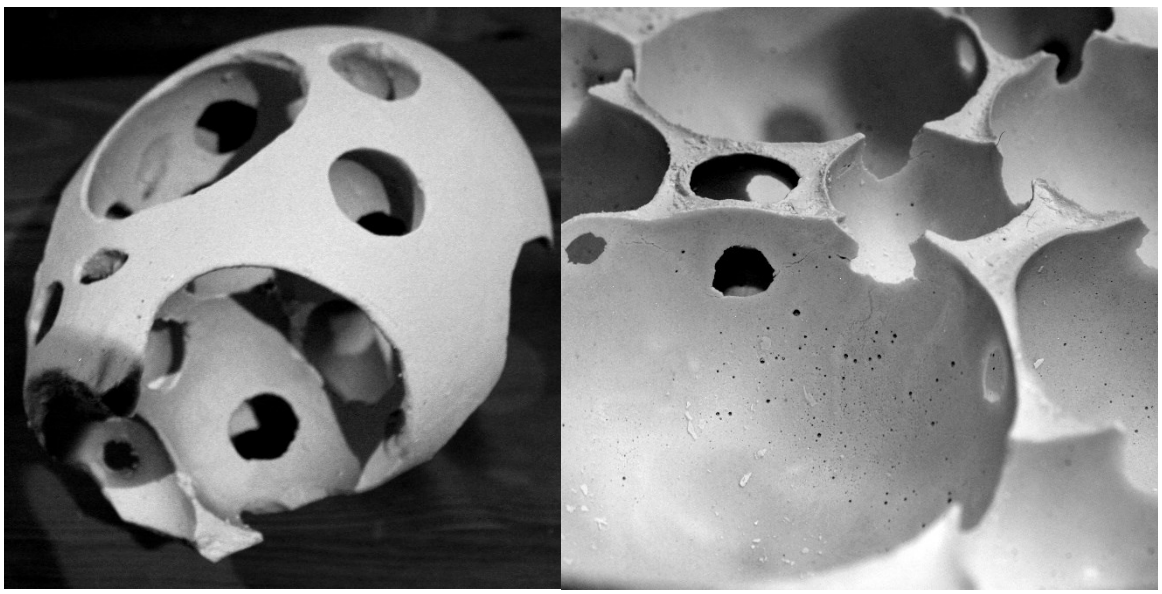

Illustration 22 Plaster castings of water-filled balloons within balloons

This casting technique revealed some issues concerning the controllability of form, while the balloons could be placed prior to casting they would inevitably shift as the balloons are stretched and compressed. Additionally, fine details were lost because of the inability of plaster to dry completely while in the form resulting in a soft and messy cast. This simulation of the porous cellular structure of cancellous bone appears somewhat convincing but fails to take into account the forces that actually determine the structure.

This brings us back to the issue of imitation and mimesis. The problem with this experiment is that it attempts to imitate the appearance of bone structure rather than imitate, through mimesis, the process that creates the structure of bone.

6.1.2 Voronoi

Voronoi are tessellations[5] where each shape (tile) is defined by a seed point and for each seed there is a corresponding region that consists of all points closer to that seed point than to any other; this regions of points is the Voronoi cell. The Voronoi cell for each defining point is a convex polygon that is modular but not repetitive. Voronoi are geometrically related to foam-like structures such as sponges, bone tissue and crystals and similar patterns can be seen in butterfly wings and leaf venation.

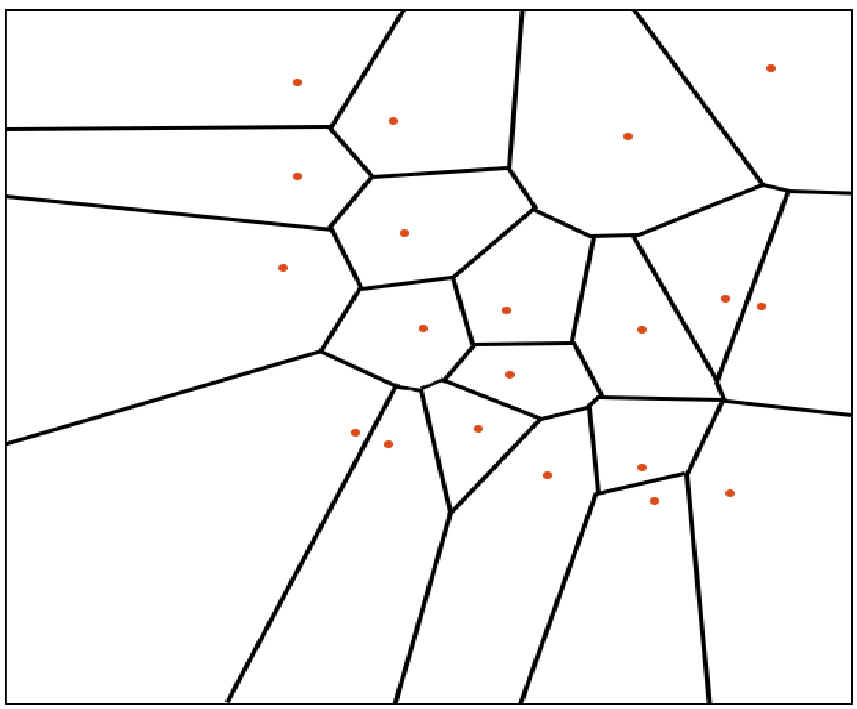

Illustration 23 Voronoi diagram showing cells and corresponding seed points

[5] A tessellation is the complete covering and patterning of a plane or space with repeated shapes without gaps or overlaps.

The overall shape is defined as a pattern of other shapes and emerges from the configuration of neighboring cells. The size and edges of the cells are sensitive to changes in local conditions. Due to this relationship of the whole to its parts Voronoi have a parametric quality that allows the overall pattern to be adaptive and yet still modular. It effectively functions as a bridge between form finding and material behavior.

These types of tessellations have become useful in architecture for breaking up complex surfaces into manufacturable shapes. The ability to control the actual shape of the cells is limited, but repetitive patterns can be made by a regular spacing of seed points. Voronoi can be used in analyzing spatial distributions because of their adaptability to locally contingent conditions.

6.1.2.1 Case Study: Three Dimensional Voronoi

Three-dimensionally, a Voronoi tessellation closely approximates a sponge-like pseudo-foam structure due to its random cellular generation and linear growth (Gibson and Ashby, 1997, 33). In order to generate this pseudo-foam, a bounding volume is specified and the cell seed points are generated randomly to fill the volume with the desired number of cells. The amount of cells generates both the foam density and average size of each cell.

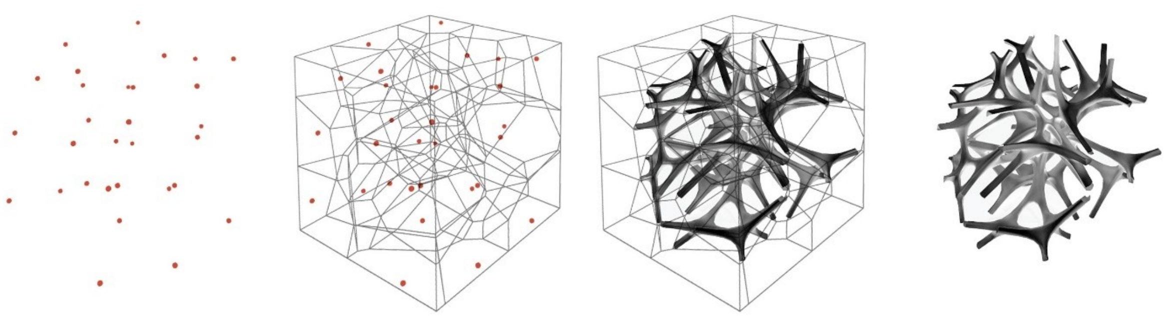

Illustration 24 A randomly generated bone-like 3d Voronoi tessellation

While convincingly bone-like in appearance the final structure is difficult to control and lacks the anisotropy of natural cellular materials making it less suitable for directional loading. Seemingly little research has been done in applying Voronoi to structural optimization, but it offers the potential for use in analyzing static systems where the cells deform under loading conditions. Using an iterative generation of Voronoi cells a solution could be found that produces a stable and optimized load-bearing structure with high strength-to-weight ratio by efficiently redirecting forces through cell vertices.

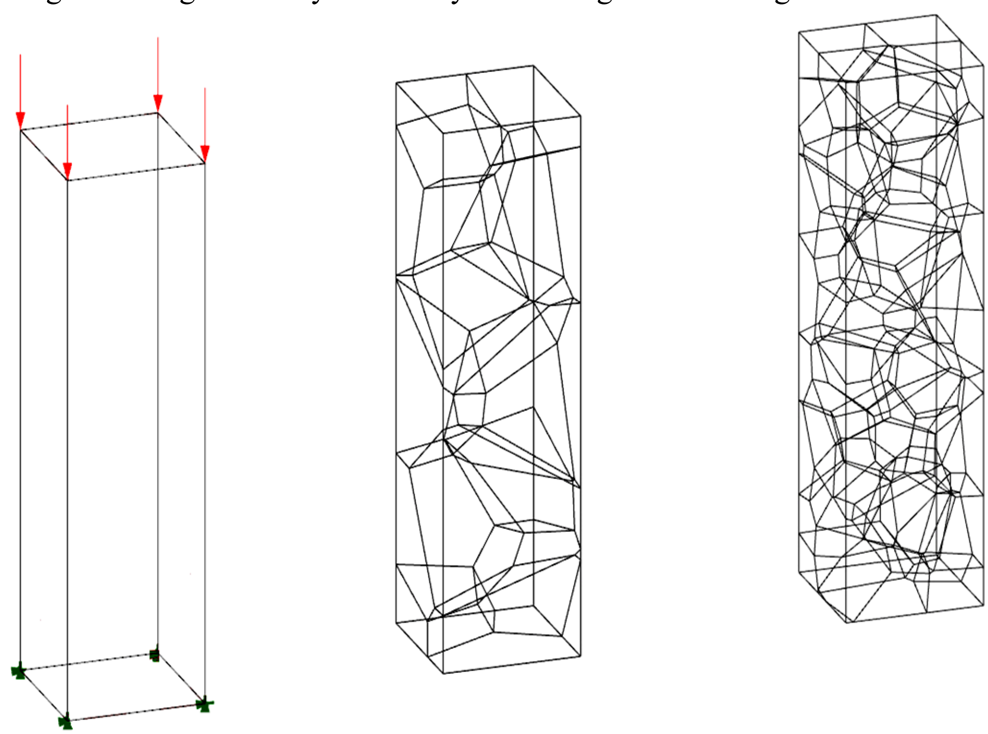

Illustration 25 A voronoi structure that minimizes deflection by iteratively manipulating seed points

The example shown above iteratively alters the seed points of the voronoi cells within a given boundary until it converges on a solution that minimizes structural deflection.

Its performance as a structure is limited by the ability to act as a coherent system of interconnected members which can only be achieved through iterative modelling. A three-dimensional Voronoi is able to alter structure and topology simultaneously so there is no way to control the final form; they are too variable. Because of this they are not hierarchically structured enough for architectural use. These limitations suggest that this process may be more suitable for developing an initial geometry as a starting point for further rigorous optimization or as a means of creating a lightweight and high-strength inner structure within a form suitable for 3d printing.

6.2 Digital Fabrication

Complex geometry has existed in architecture long before the advent of computers. The potential for complexity has reflected the available construction methods of the time. We are now able to explore complex form generation at quickly and with high precision, beyond even our capability to construct it.

Digital tools now provide designers with vast possibilities for creating forms with rapid prototyping processes which allow a nearly direct translation of a digitally modeled form into a physically fabricated one. But these processes are often limited to fabrication of objects with homogeneous materials. The following examples will look at the issues in fabricating digital architecture and integrating the digital into the construction process. These projects mix cutting-edge digital design with traditional construction methods.

6.2.1 Shigeru Ban's Centre Pompidou-Metz

The annex in Metz for the Pompidou Centre was built to house an art museum and theater. The main design feature of the annex is its roof, which is made from laminated wood woven in a hexagonal pattern. The roof is covered in a Teflon-coated glassfibre membrane to allow natural light to filter into the interior spaces.

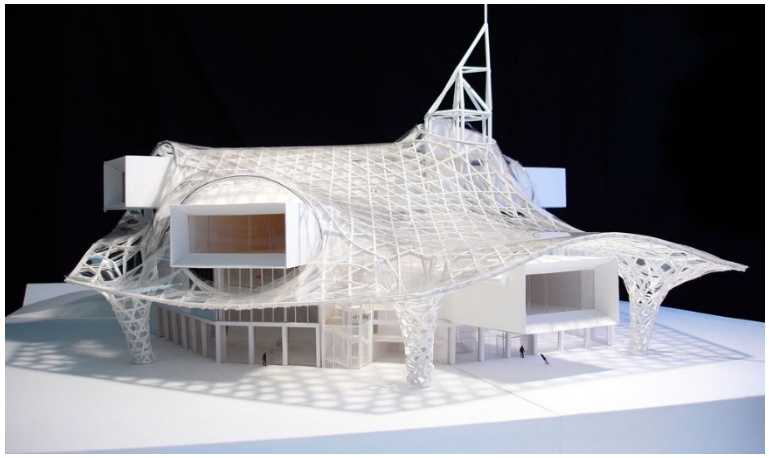

Illustration 26 A model for the Pompidou-Metz showing intersection of the roof with the volumes (shigerubanarchitects.com)

The main galleries are a series of cantilevering rectilinear tubes that intersect the roof and float above the orthogonal space below. The complex curvature and joinery of the laminated timber roof could not have been designed without the use of NURBS geometry and CNC milling, but the rest of the building (intentional or not) is rather traditional.

Illustration 27 The intersection of walls and roof of the Pompidou-Metz (shigerubanarchitects.com)

The galleries spaces are rectangular boxes and the atrium beneath the roof uses orthogonal geometry to enclose the space by simply abutting the curved roof.

6.2.2 Toyo Ito’s Opera House

Perhaps one of the best examples of large-scale architecture that confronts the difficulties of translating complex digital shapes into the built realm is Toyo Ito’s Taichung Metropolitan Opera House. Construction commenced in late 2009 and is scheduled for completion in 2015. The building is comprised of a single continuous curved surface that acts as a structure and links together interior and exterior spaces; its appearance resembles that of a sponge.

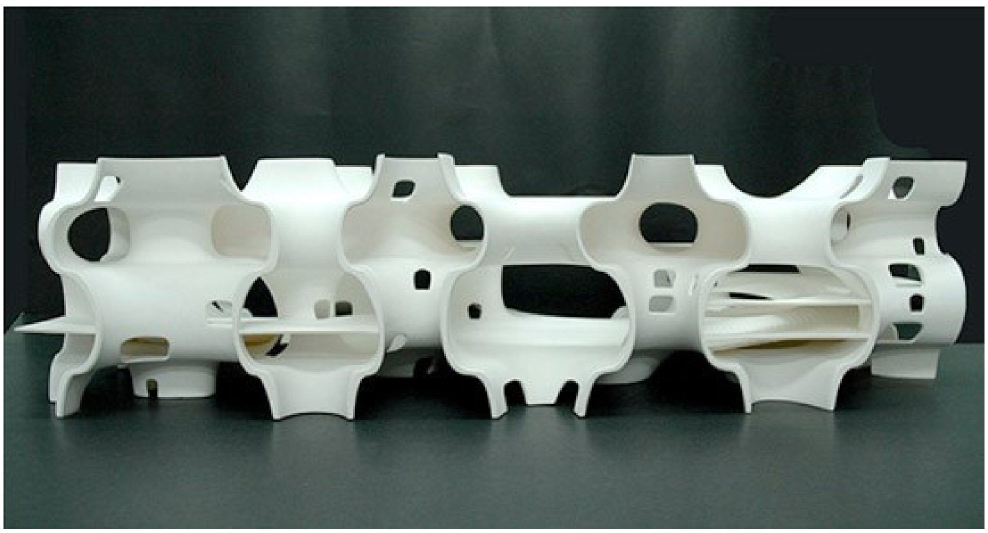

Illustration 28 Structural model of the Taichung Opera House (www.toyo-ito.co.jp)

Rather than creating complex doubly-curved formwork, the structure was made using shotcrete (spray concrete) on a temporary steel structure and expanded metal mesh. The concrete was then plastered by hand for a smooth and even finish.


Illustration 29 Construction process of the complex curved concrete form (www.toyo-ito.co.jp)

While the structure makes no distinction between floor, ceiling and walls flat slab floor are still needed, as are stairs. It is evident from images and sections that these are separate from the main structure and conflict with the formal tectonics. Additionally, the shape is very 'digital' but the construction method is far from it. The inaccuracy of shotcrete and the need to finish the structure by hand is time consuming and laborious. Although scale is always an issue perhaps parts could have been digitally fabricated and then assembled on site.

6.2.3 Implications of Digital Fabrication in Large Scale Construction

Digital production as a creative medium in architecture comes with many new possibilities and limitations, but the digital design process it still not fully integrated with the construction process. There is still room for innovation in this gap between design and building – digital fabrication.

Digital fabrication is a way of making that uses data to control the process of fabrication which is then executed by computer-driven CAD/CAM tools like laser-cutters, water jet and CNC routers. This precision allows the fabrication of complex geometries without affecting the cost; fabricating unique components requires as much effort as fabricating many identical ones. We are seeing a shift away from standardization towards differentiation because CAM is not just a manufacturing facilitator but an integral part of the design process.

At the moment, digital fabrication remains at the scale of applied research, that is to say smaller scale design like furniture and pavilions. Digital fabrication, like typical construction, still relies on assembly and needs an understanding of construction technique as the method of making informs the aesthetic. The following sections will look at 3D printing techniques as potential fabrication methods for construction.

6.3 3D Printing

Three-dimensional printing is achieved by a variety of methods (selective laser sintering, fused deposition modeling) which currently lend themselves mainly to the creation of model making in architecture. This fabrication process is one of the most direct translations of digital to analog, it reduces the element of human error and imprecision, but it currently does not address the material or size constraints of large-scale construction. Typically, finding a structurally optimized and geometrically defined form was a necessary condition to translate into building. With advances in computational tools we are basically unrestricted in formal design, but the realization of these forms requires linking the design to the logic of manufacturing processes.

6.4 Additive Manufacturing

Additive manufacturing (AM) is a layer-by-layer additive fabrication process that builds up three-dimensional objects by the automated curing and deposition of sequential layers of material. This process has the ability to create complex internal structures within the form. These machines fall under the classification of 3D printers and are typically based on using an aggregate and binding agent.

6.4.1 3D Printing for Construction

Digital fabrication is easily applied to smaller architectural elements like cladding panels, furniture and joint details. Building at the scale of a pavilion can be fully designed and manufactured digitally but extending this process to architecture at a larger scale is problematic. Purely digitally designed and manufactured architecture is currently very limited in its use in large-scale architecture. This is due in part to cost, materials, manufacturing size limitations and most importantly assembly.

The most promising development in digital construction fabrication may be the 3D printing of concrete which offers the possibility of constructing complex forms without extensive formwork. Construction grade 3D printing has counterparts to small scale 3D printing. One system, like D-Shape discussed below, relies on selective solidification while others are based on extrusion.

6.4.1.1 D-Shape and Selective Solidification Printing

One of the prospective systems for use in architecture is D-Shape, developed by Dini Engineering, which is able to ‘print’ forms as large as 4x5x5 meters using a concrete alternative that is suitable for load-bearing.

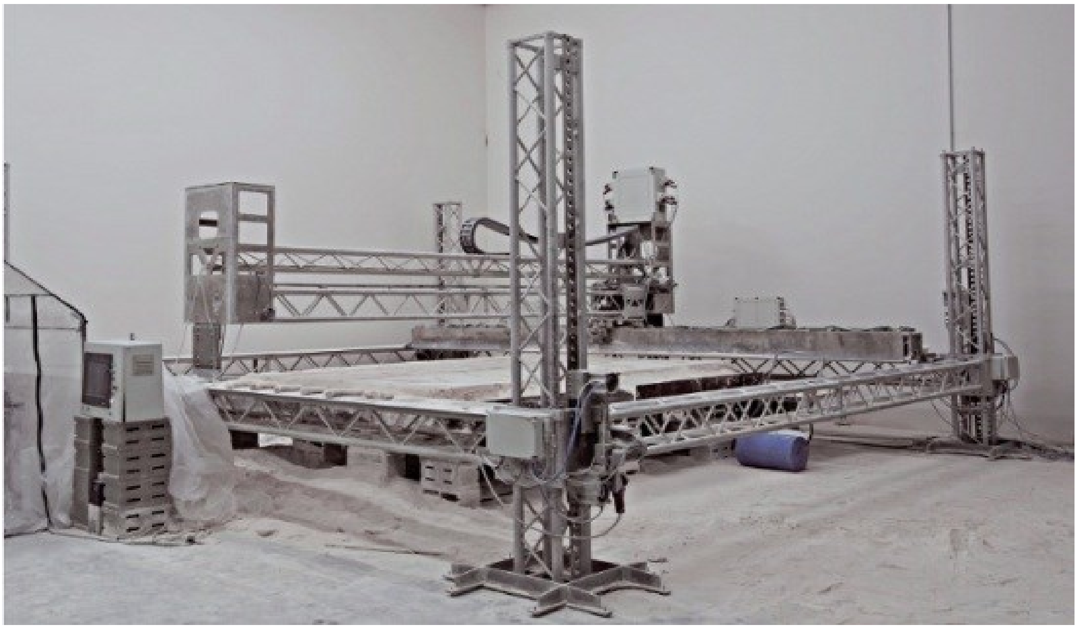

Illustration 30 The D-Shape printing bed (d-shape.com)

The D-Shape printer is essentially a massive plotter, with a square frame that lifts along four columns. Each corner of the frame is equipped with a pneumatic motor to allow the frame to rise as it prints. A beam is mounted on the frame and supports the moving printing head. The print is driven by the stereolithography file (STL) that is imported into the CAD/CAM software.

The printing process, known as selective state change, uses a magnesium oxide stone powder aggregate which is selectively solidified by chemical activation with the liquid binding agent. During this process the aggregate transforms from granular powder to sandstone, which takes nearly one hour. The catalyzed material does not need to solidify before the next layer is printed as the unbonded aggregate acts as support during the printing process allowing for the creation of freeform shapes (Soar and Andreen, 2012, 130). This printing technique is limited mostly by the material strength and the print resolution.

Shown below is the 3 meter tall prototype for the *Radiolaria Pavilion* developed to demonstrate the capabilities of the D-Shape printer. A full size 8 meter tall version is planned for construction and installation in a roundabout in Pontedera, Italy.

Illustration 31 The Radiolaria prototype designed by Shiro Studio and fabricated by D-Shape (d-shape.com)

6.4.1.2 Extrusion Printing

Extrusion based printers work by depositing material in thin layers until a structure is built up to the desired height. It is worth noting a drawback of these printers is that due to the extrusion process large overhangs are impossible to print.

The Freeform Construction Project at Loughborough University has partnered with Buro Happold and Foster & Partners to develop an extrusion based concrete printer. This system has the capability to print with a cement based mortar and can precisely control the placement of voids and cavities for placement of building services. Using this method sections of the building could be printed then assembled on-site. At the moment this system seems to be developed at a scale for printing cladding and curved panels.

Illustration 32 Curved wall printed by Freeform Construction (buildfreeform.com)

Another extrusion based large-scale concrete printer is being developed by researchers at the University of Southern California and is known as Contour Crafting. It uses a computer-controlled gantry to print structures in layers of quick-setting concrete.

Illustration 33 Rendering of the Contour Crafting construction process (contourcrafting.org)

Contour Crafting can make use of in situ construction material saving time and costs associated with transportation. Labour costs are nearly non-existent and construction material waste is minimized. When ready this system claims to be able to erect a two-storey house in less than 24 hours; potential reducing the construction costs to a fifth of what they currently are.

In addition to large-scale printing of concrete, plans are underway in the Netherlands to 3D print a complete building using extruded bioplastic, which is essentially an enlarged version of desktop 3D printing. Dus Architects plan to print the building in sections then stack and assemble it like LEGO.

While D-Shape is most suited to large scale structure, extrusion based systems, such as Freeform Construction or Contour Crafting, have the ability to print at finer resolutions more suitable for interior finishes but not freeform shapes.

Eventually, Additive Manufacturing will have the possibility to grade the material properties in the structure similar to how it occurs in nature. For example, bones are not composed of a separate outer layer and a porous center, instead the material smoothly transitions its structural properties throughout the structure. Eventually we will be able to design the structure at such a fine scale that the optimal amount of material and desired properties exist throughout the structure.

6.4.2 Graded Materials

Typical construction materials have homogeneous material properties and do not take advantage of the ability to increase strength at reduced weight and material costs. There have been developments in materials with variable density for possible use in construction by using additive manufacturing techniques. Functionally graded materials have a spatially varied composition determined by external conditions. Bones display this property by having a continuous structure with varying density.

Much of this research is coming out of MIT's Mediated Matter Research lab, which is looking to cancellous bone as a model for the development of variable-density cement foams and 3d printed concrete. Variable density is achieved using a dynamic mixing chamber and robotic extruder to mechanically foam the concrete (Oxman, 2012, 94).

Illustration 34 Variable density concrete sample from MIT Media Lab

Introducing density gradients in concrete could increase the strength of structural elements, reduce the material waste and increase the thermal value. Digital analysis of structures could be integrated into the design process by directly informing the placement of material in relation to analyzed stresses.

6.5 Biological Manufacturing

An extreme example of taking cues from natural growth processes for manufacturing is the Baubotanik project from the Institute for Architectural Theory and Design (IGMA) at the University of Stuttgart. This project was developed with the aim to transform trees into hybrid natural/man-made structure that responds to environmental and practical conditions. By binding and joining the plants in particular ways, the bark tissues can be merged together to control the overall structure. The plant also grows in response to the fastening by thickening at the joint to reduce stresses. The flow of fluid and forces needs to be optimized within the structure to take advantage of the tree's shape optimization.

Illustration 35 The creation of structural joints by merging plants (IGMA)

The Baubotanik Tower was created in 2009 using this method, requiring the use of 400 willows. The structural scaffolding requires temporary supports until the plants can withstand the loading capacity, which they estimate will take 5 to 10 years due to the unpredictability of the growth process (Ludwig, Schwertfreger, and Storz, 2012, 86). As it grows the overall structure will not change but it will become less homogeneous, a tree canopy will develop and close in the top while the bottom of the plant structure will become more like a diagrid superstructure.

Illustration 36 The Baubotanik Tower in 2009 (IGMA)

This project is an exciting step towards the possibility of growing our buildings but has some major disadvantages: time, fragility, and unpredictability. Perhaps the study of how these plants respond to restraints and connections as a means of re-directing forces through a structure may eventually be viable in application to architecture.

6.6 Construction Manufacturing

It is the beginning of the end of the disparity between a designer's vision and the limitations of the construction industry. Design software has exceeded the physical production of form but now design and fabrication are converging. The previously discussed D-Shape construction method has proven capable of creating highly complex geometries at full scale. The use of optimization software seems suited to this construction method as it can fabricate complex geometries with no cost premium and offers the possibility of creating delicate structures with similar strength to weight ratios as bone.

Like bone, it is possible to include tensile materials within a 3D printed structure in a way that follows stress paths in the form by using of post-tensioned steel. Internal conduits can be made within the structures to accommodate tensile materials; acting similarly to collagen fibrils within bone. Although we can replicate some of the responsive qualities of bones using optimization software, it will be a while before we can create responsive structures that adapt to changing stresses during and after construction.

7 Chapter: Topology Optimization

“Evolution is to nature what optimization processes are to the designer.”

-Neri Oxman

Topology Optimization is a mathematical approach to optimizing material layout within a design space, for a particular set of loads and support conditions, with the intent of minimize or maximizing certain functions (Bendsoe and Sigmund, 2003). This is typically used early in the design process to improve performance and save on development time. Optimal structural design has always been important in construction with demands for lightweight, inexpensive, and strong structures. It is also becoming more important with respect to the increasingly limited material resources and the environmental impact of construction.

Topology optimization is typically used for discrete structures, such as trusses and frames, to find the optimal spatial placement and connectivity of the members by placement and removal of material within the design domain. Its application is not limited to any particular scale.

7.1 Finite Element Method

Finite Element Method (FEM) is a calculative technique for finding approximate solutions by eliminating those that do not fit the boundary of a function. This method connects together many smaller equations, known as finite elements, in order to approximate a more complex equation. FEM utilizes mesh discretization which subdivides a continuous domain into discrete sub-domains (elements). Essentially any shape, two or three dimensional, can be represented by a collection of smaller, simpler polygonal surfaces for which individually the loading calculation can be more easily computed. These elements are connected through nodes, the vertices of the polygonal elements, which give common boundaries to adjacent elements in the mesh and allow for a continuous solution to be applied within the domain. Solutions are resolved per individual element, by measuring the displacement of elements at the nodes subject to a load, then assembled to predict the overall behavior of the object. The solution is an approximation given by the displacement of the nodes; by increasing the number of elements the solution will converge on the true value.

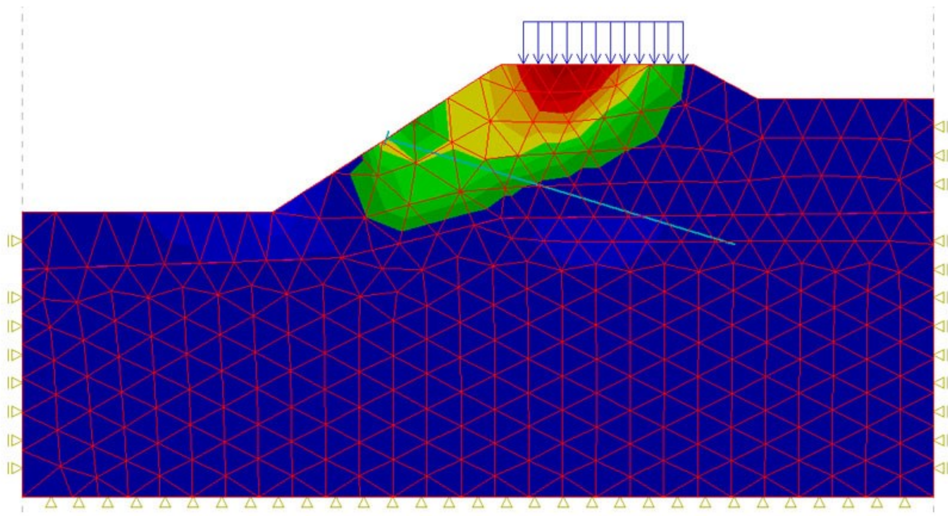

Illustration 37 FEM mesh showing subdivision into polygonal elements (Wikimedia Commons)

In engineering the application of FEM is known as Finite Element Analysis (FEA) and is commonly used in structural design to increase strength and reduce the weight of an object. For use in structural analysis the steps are as follows:

- model the geometry
- mesh discretization of the geometry into elements
- specify material properties for elements (Young's modulus of elasticity and shear modulus for stresses)
- specify boundary, initial, and loading conditions
- solution computation and visualization (output as contour lines or colours)

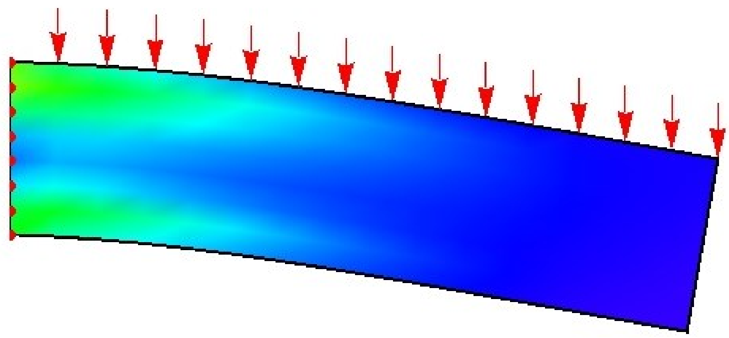

Illustration 38 Finite element analysis of a cantilevered beam with stresses visualized by colour (wolframalpha.com)

FEM is the fundamental algorithm used in the following topology optimization approaches.

7.2 Computer Aided Optimization

The axiom of constant stress was coupled with the finite element method and developed into a computer-aided shape optimization (CAO) by biologist Claus Mattheck at the Karlsruhe Research Centre in Germany; taking inspiration from the growth of trees. CAO creates an even distribution of stresses through adaptive growth so that no area is over or under loaded. Areas of high stress are selectively reinforced; this occurs mainly on the surface layer of the model much like in trees. However, using this method, the quality of the final shape depends on the initial topology because CAO does not create new holes it can only shape existing contours. To address this problem Mattheck turned to the structure of bone.

7.3 Computer Aided Internal Optimization

In nature, the optimization of structures doesn’t stop at the external form, it simultaneously considers the optimization of the material internally. The digital equivalent of this is called Computer Aided Internal Optimization (CAIO). In nature most structures are made of composite materials whose fibers are arranged in the direction parallel to the stresses reducing the shear stress between fibers. By similarly arranging fibers we can take advantage of stress distributions and minimize shear and transverse stresses, this is especially important around openings. Wood and bone are a notable examples of this optimal fiber arrangement.

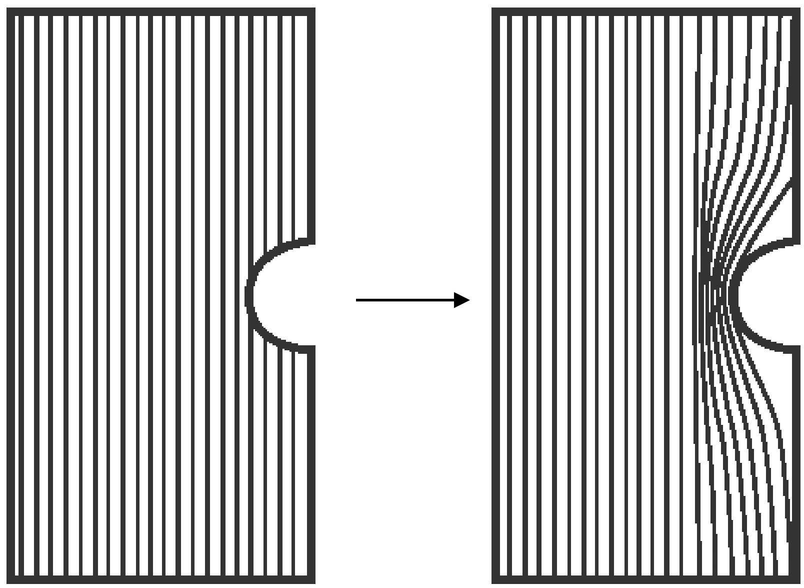

Illustration 39 Before and after CAIO optimization of fibers in a notched tensile plate

Using a stress distribution based on FEM, the CAIO method computes the new orientation of the stresses for each element as well as the principal stress trajectories. This is run iteratively until the axes of each element are rotated to coincide with the stiffest orientation thus determining the optimal orientation of the fibers. (Mattheck, et al., 1993, 308)

7.4 Soft Kill Option

Bone is extremely well optimized to carry loads owing specifically to its ability to adaptively remodel itself under changing loading conditions. Higher stresses lead to areas of higher mineralization and vice versa. This subtractive optimization reduces matter where it is not needed creating holes in unloaded zones. The computational process developed to mimic this is known as Soft Kill Option (SKO). Steps required in this process are outlined below.

- A design area or form is roughly shaped, ideally oversized as the function can only remove material not add it. A finite element mesh is applied to the shape.
- Finite element analysis is calculated with a constant Young's modulus (E), the modulus of elasticity, using anticipated loads and support points within the given form in order to calculate stress distribution
- Young's modulus is varied as a function the stresses (E=f(s))
- New stress distribution is calculated with the same load but using the varied Young's modulus (E)
- Repeat until the areas of high and low Young's modulus are sharply defined. Non loaded areas are removed ('killed')

The SKO method begins by setting the initial limiting dimensions, the "bounding box", of the object. External loads are applied along with any support or restraining conditions. The finite element method (FEM) is applied to derive the calculations for stress and strain within the object. According to the calculated stress, the Young's modulus is increased in areas of high stress and reduced in under-loaded areas. The Young's modulus is compared to a reference stress, the desired stress level in the structure, which is used to determine whether the value is increased or decreased. So the load bearing areas are reinforced and any non-load bearing areas are gradually eliminated. Any remaining notch stresses are then removed by the application of the CAO method which shrinks any still remaining non-load bearing zones.

The combination of FEM, SKO and CAO is able to mimic the iterative, evolutionary structural optimization found in nature and create resistant, lightweight objects with maximum performance for minimum weight.

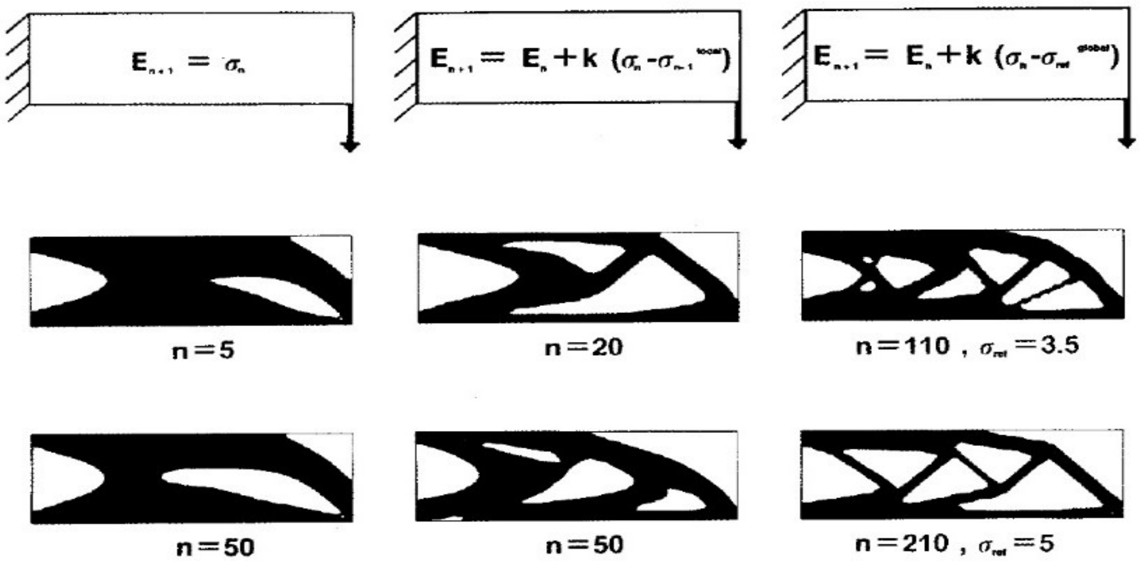

Illustration 40 Optimization iterations of a cantilevered object using SKO (Baumgartner, et al.)

7.5 Evolutionary Structural Optimization

Evolutionary Structural Optimization (ESO) is a design optimization method that gradually removes underutilized material from a structure using Finite Element Analysis (FEA). This is repeated until the resulting design is fully stressed - all the members support the same maximum stress. Using this method the resultant structure evolves towards its optimal, which is the lightest and most rigid, shape. ESO was developed in the early 90s by professors Mike Xie and Grant Steven from Victoria University of Technology and University of Sydney respectively.

The stress level is measured at each element using the von Mises stress[6] value giving the average value of all stresses in the given stress planes. The under-stressed material is removed using a rejection ratio criterion (RR) by comparing the stress of a given element ($\sigma^{vm\ e}$) to the overall maximum stress ($\sigma^{vm\ max}$) of the structure. Material that satisfies this condition is removed at each iteration.

$$(\sigma^{vm\ e} / \sigma^{vm\ max}) < RR\ i$$

This process of FEA and element removal is repeated using the same value of RR *i* until a steady state is reached, with no more elements being deleted. When this steady state is achieved an evolutionary rate (ER) is added to the rejection ratio.

$$RR\ i{+}1 = RR\ i + ER$$

With the rejection ratio increased the iterative element removal continues until another steady state is reached. The evolutionary process continues until the desired optimum is acquired; this may be a target stress or stiffness value for the final structure. A history of the process is recorded so that the most suitable structure for the desired objective, lightest or strongest, can be chosen (Huang and Xie, 2010). The ESO procedure can be summarized as this:

- Discretize the structure with a mesh of finite elements
- Perform finite element analysis for the structure
- Remove elements which satisfy the rejection criterion

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[6] Von Mises stress (σ^{vm}) is a yield criterion in a used to predict failure in a ductile material, it is derived from the strain energy that develops at a particular point in a material. A material is said to yield when σ^{vm} reaches the yield strength of the material (S_y) (Leckie and Dal Bello, 286)

- Increase the rejection ratio by adding an evolutionary ratio
- Repeat until the desired optimum is reached

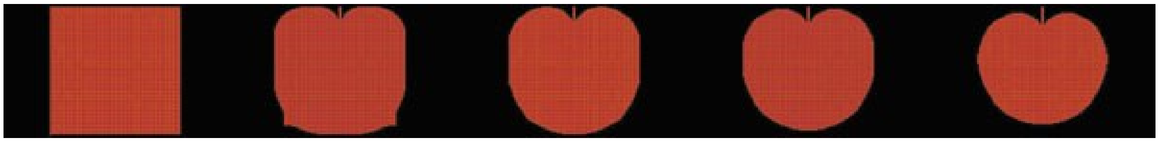

Illustration 41 ESO results of a suspended object subject to gravity (Xie and Steven)

The image above shows the evolution towards an optimal shape for a suspended object subjected to gravity. Removing the least stressed material from the surface gives us a final shape with a uniform surface stress. The resulting shape appears strikingly familiar to that of various hanging fruits.

The ESO procedure is very similar to that used in SKO, both utilize the FEM algorithm for analysis and produce similar results. The processes of ESO and SKO are very similar to the self-organization of bone tissue and have been used to accurately predict bone remodeling in the creation of artificial bone substitutes (Chen, Pettet, Pearcy, and McElwain, 2007).

7.6 Bi-directional Evolutionary Structural Optimization

The Evolutionary Structural Optimization method did not allow removed elements to be restored and so structural elements may be removed prematurely causing an irreversible and potentially non-optimal change. To improve on this process, a bi-directional ESO (BESO) method was developed allowing material to be added and deleted simultaneously. With this improvement the computation time is reduced and requires fewer iterations. The disadvantage is that BESO needs to start with a basic speculative structure, a ‘best guess’ design, that contains the minimum amount of elements needed to support the load cases prior to optimization; it then grows into the optimal design (Huang, Xie and Burry, 2006).

8 Chapter: Topology Optimization Software

8.1 Topology Optimization Software

As seen in the previous chapter, the process of topology optimization stems from the way that natural structures develop under load by distributing and/or redistributing material in response to internal and external forces.

Numerous digital optimization tools using this logic have been developed in recent years: Altair Engineering's solidThinking Inspire and OptiStruct, Autodesk's Inventor Optimization, Siemens PLM Software's NX Toplogy and NX Shape Optimization, and WithinLab's Enhance software. The majority of these are used in industrial design cases, optimizing components for automobiles and airplanes, driven by the need to reduce weight.

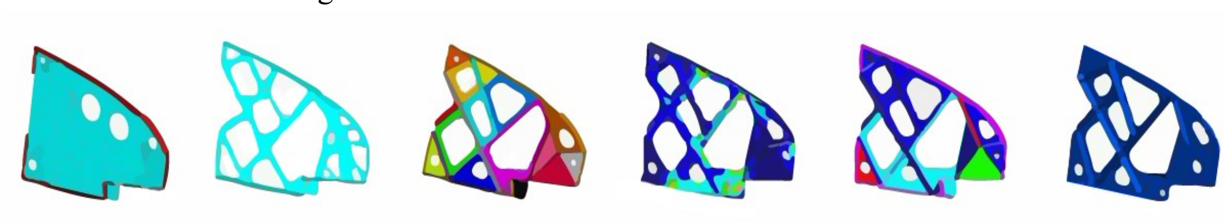

Illustration 42 Aeronautic ESO optimization of the structure within an Airbus A380 wing (Altair Engineering)

8.1.1 Case Study: Lighting Nodes by Arup

A very recent example of the use of topology optimization software comes from Arup as a means of developing a complex lighting structure that uses high-tension cables held together with 1,000 individual steel nodes (shown below).

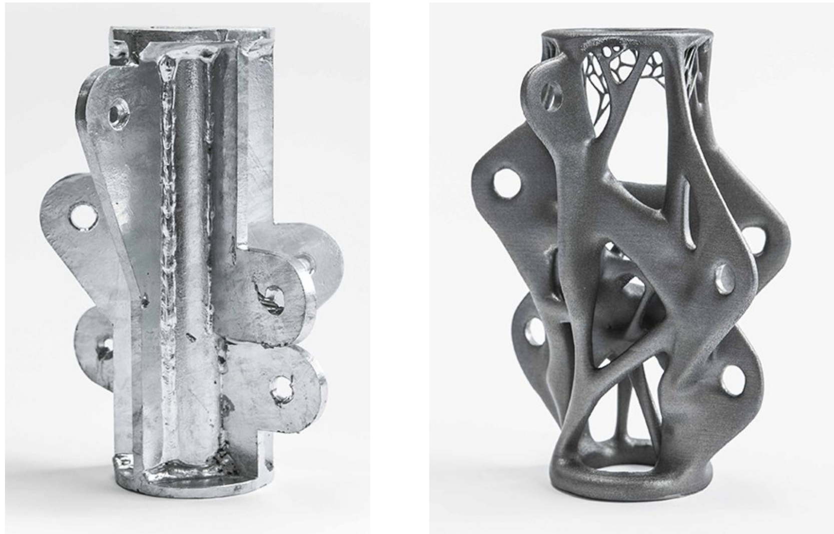

Illustration 43 Traditional welded node design compared to the optimized and 3D printed node (Arup.com)

To create this optimized node Arup collaborated with WithinLab software, CRDM/3D Systems and EOS to model, optimize, and build the node. WithinLab's FEA software was used to optimize the form within its existing boundary.

The resulting steel node is too complex to be hand welded and instead was 3D printed in construction grade steel. The nodes are 3D printed in steel using a manufacturing technique known as Direct Metal Laser Sintering (DMLS). By using DMLS Arup is able to turn a complex assembly of pieces into a single part, reducing assembly time and improving strength. Additionally, compared to the traditional welded design it is 15% lighter as nothing in the design is superfluous.

These nodes were designed to be mixed with traditional construction components as this process is not yet ready to be used at the building scale. As well, the cost is a limiting factor, traditional manufacturing is still cheaper but Arup is confident this will change soon and we will begin to see increasingly more 3D printed construction components as it becomes more common place, more economical, and less wasteful than traditional construction methods.

8.2 Millipede

Millipede is a structural analysis and optimization plug-in developed by Kaijima Sawako and Michalatos Panagiotis for the parametric software Grasshopper. This tool utilizes BESO and SKO methods to analyze 3D volumetric models using topology optimization based on methods outlined in the book *Topology Optimization, Theory, Methods and Applications* written by M.P. Bendsoe and O. Sigmund.

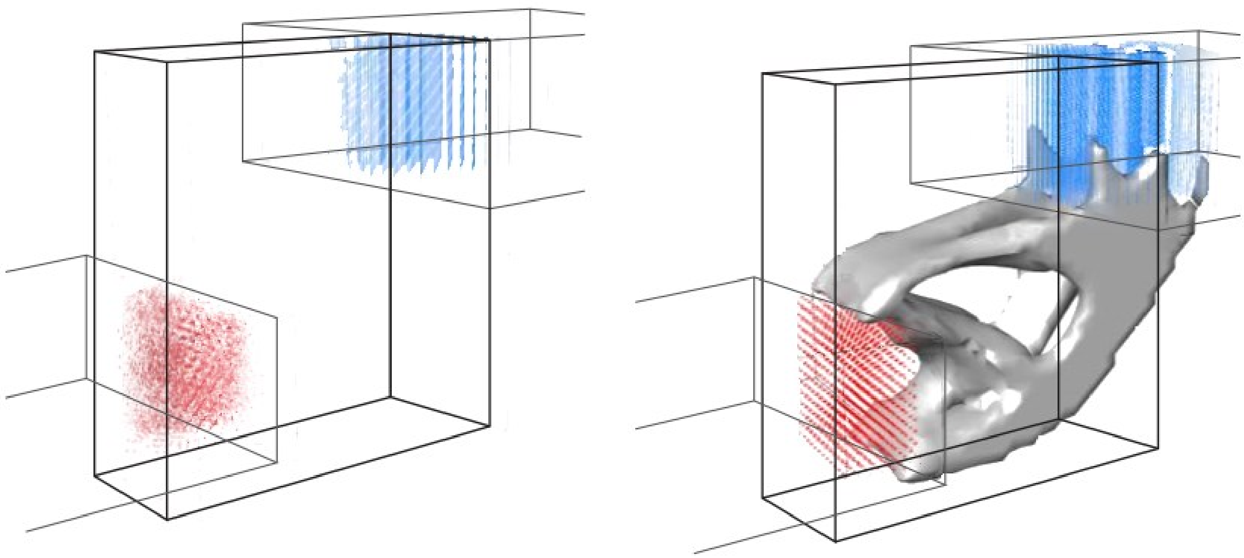

Illustration 44 Optimization of a boundary volume using millipede

It is worth noting that this software does not require the restraint of a pre-existing shape, so now the process of structural optimization can be used as design tool. Millipede will be used as the main analysis tool in the design portion of this thesis.

8.2.1 Analysis Output

The analysis performed by Millipede is based on the voxelization[7] of a domain by creating a three dimensional grid of cubic volume elements. The main domain volume establishes the boundary within which the solver places material. Additional boundary regions designate densities, voids, loads and supports to be included in the calculation. Load regions are three-dimensional vectors that represent a load in Newtons per cubic metre (N/m3). While the support component allows the user to determine the degrees of freedom represented by X, Y, and Z and RX, RY, and RZ which signify the rotation around the corresponding axes (Michalatos and Kaijima, 2011).

The resultant output is a FEA model from which you can extract data to be visualized or elaborated. The output data from the analysis consists of node and volume results as listed below:

1. Displacement vectors of the voxel nodes, representing the displacement under load.
2. Stress planes with origins at the center of each voxel aligned with the three principal stress directions.
3. Principles stress vectors are output in X, Y, and Z with positive values designating compression and negative values designating tension. X axis represents normal forces, while Y and Z represent perpendicular shear forces.

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[7] Voxels are digital volume elements that represents a position in a 3D grid. Developed for use in visualization of medical imaging.

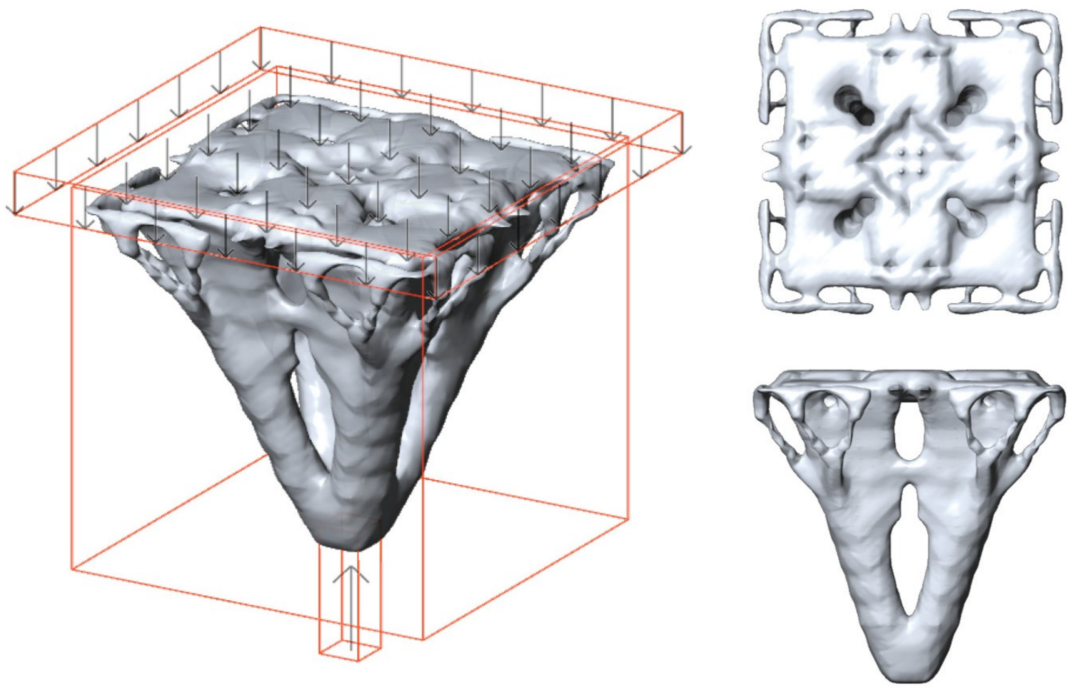
4. Von Mises stresses representing a measure of the overall stress at each voxel by combining the values of both principal stresses.
5. Density of the redistributed material from 0.0 to 1.0, void to solid, designating the density of each voxel.

The accuracy of the optimization process depends greatly on the number of iterations and the resolution of the initial voxel grid, however, as the resolution increases so does the time required to compute a solution.

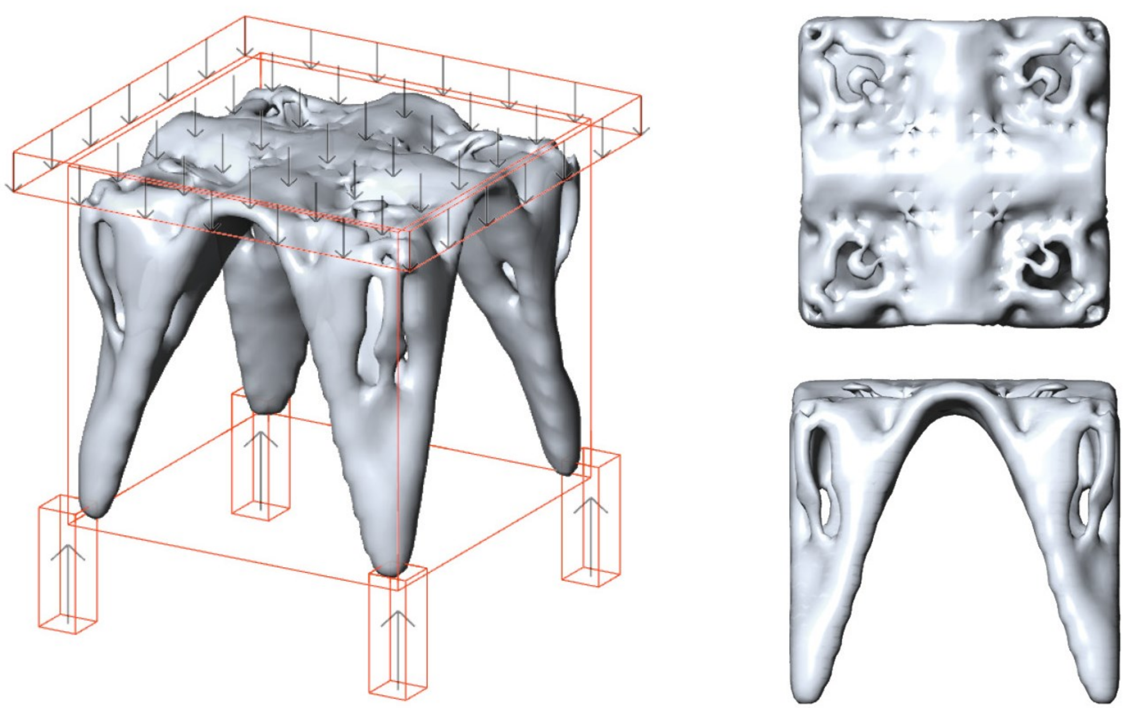
8.3 Case Study: Digital Topology Optimization using Millipede

To examine the effectiveness of this optimization algorithm several comparative tests were performed, using equivalent load cases, to show the relationship between load and support conditions. The boundary volume and load were kept identical and the support positions were moved. Each scenario was run through an equal amount of iterations (20) using the same resolution to arrive at the solution.

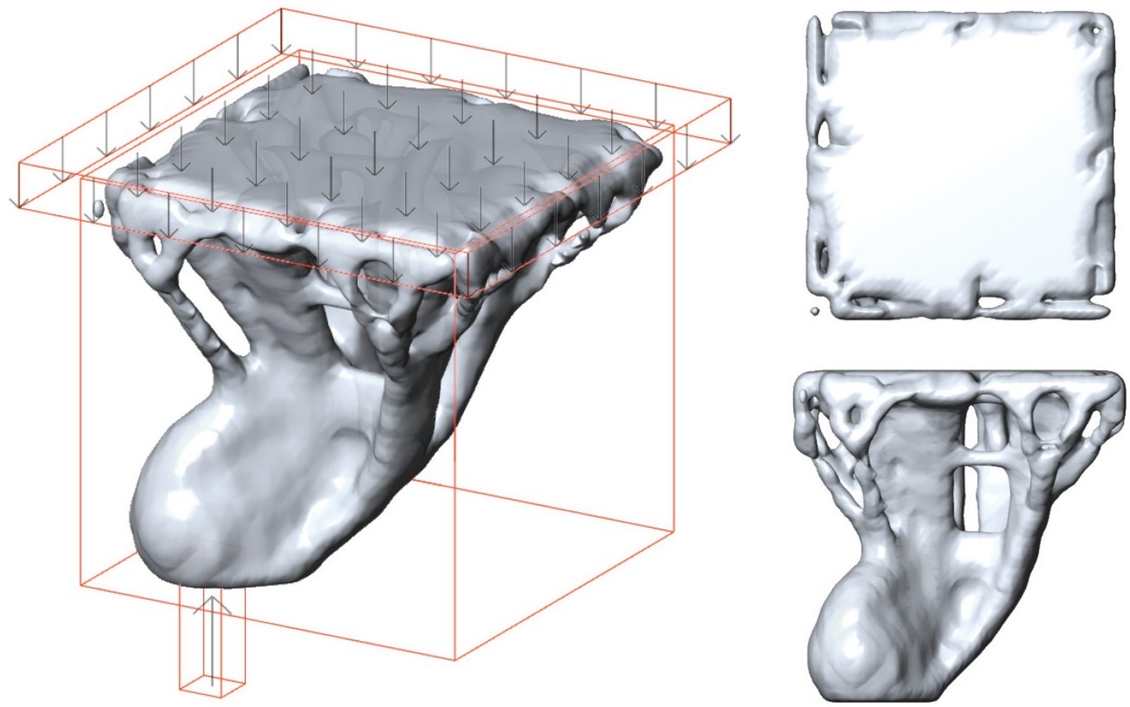
8.3.1 Uniform Distributed Load with One Support



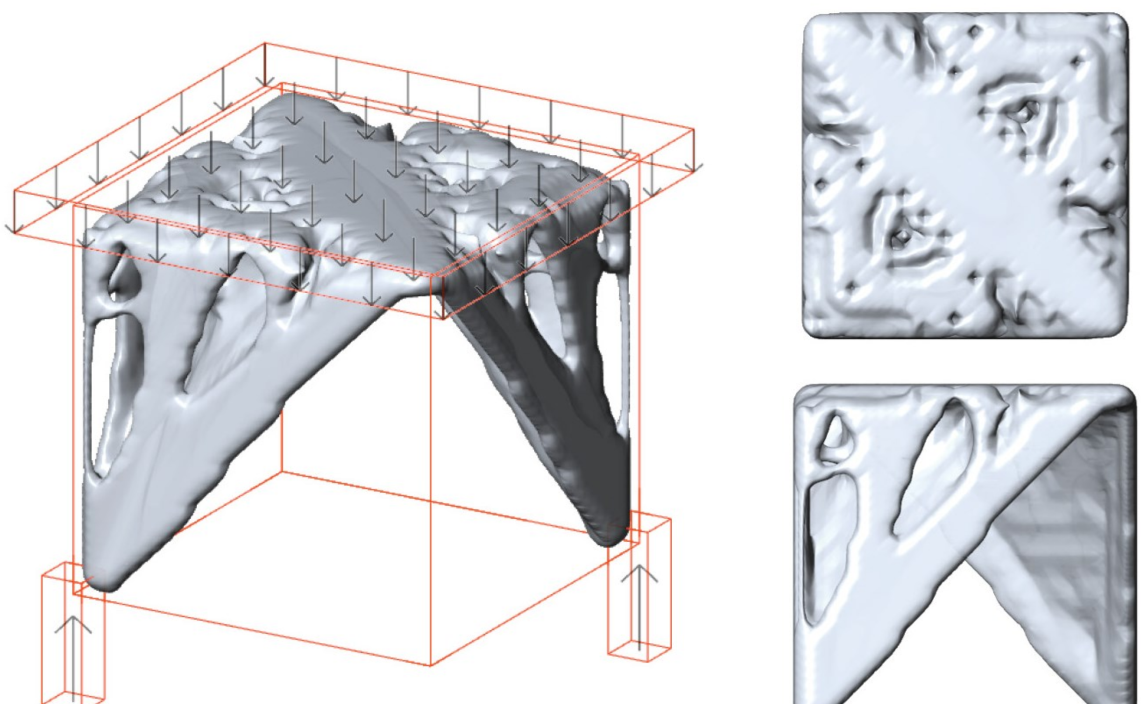
8.3.2 Uniform Distributed Load with Four Supports



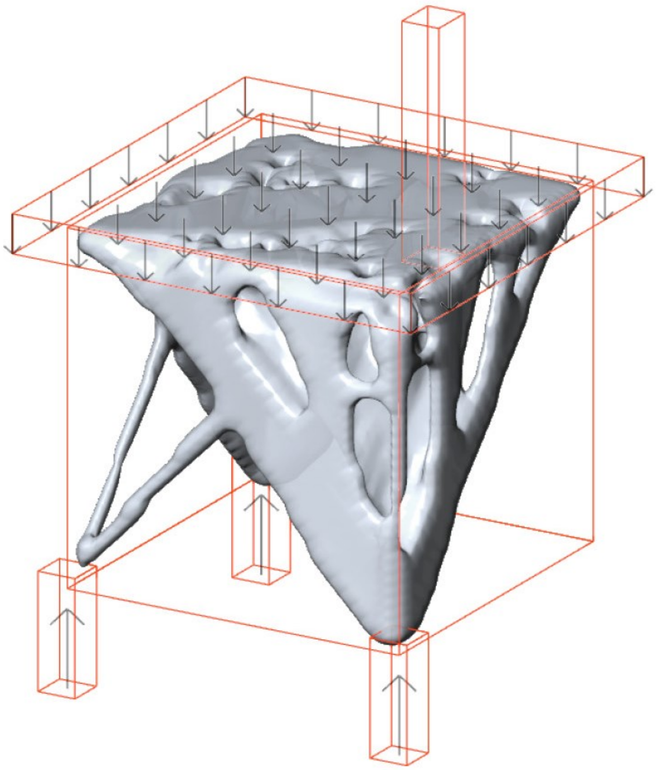
8.3.3 Uniform Distributed Load with Asymmetric Support

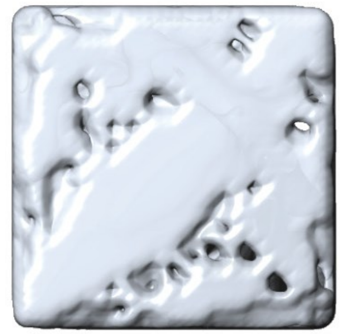


8.3.4 Uniform Distributed Load with Corner Supports



8.3.5 Uniform Distributed Load and Point Load with Three Supports





8.4 Summary

The preceding scenarios demonstrate the efficiency of the simulation and clearly show the relationship of loads to the supporting conditions. It shows the adaptation of the structure within the design boundary as it adjusts to carry the same load with varying supports. However, adding more loads and boundary conditions will increase the computing time as does increasing the resolution to get a finer structure.

Despite its speed and efficiency the output mesh is too rough and chunky for use as an architectural object. The modification of its output for finer detail and aesthetics will be discussed in Chapter 9.

9 Chapter: Design Methodology

Based on the design methodologies put forth in the following sections it is possible to develop prototypical architectural designs that utilize the generative principles of bone remodeling. The separate steps are outlined below.

9.1 Define Geometry

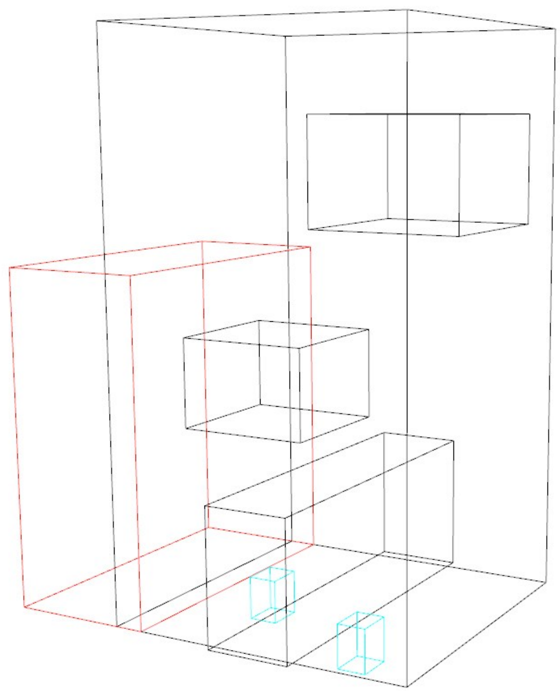


Illustration 45 Initial volume geometry

Firstly, an overall boundary volume is designated along with void spaces for architectural programming, related supports, and loads (all volume geometry). The geometry used in the finite element analysis is not the final form but rather acts as a catalyst for the emergence of other forms.

9.2 Analysis

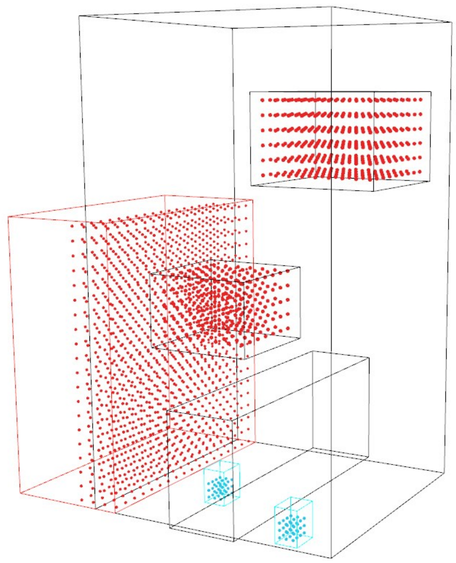


Illustration 46 Load, support and void volumes defined for analysis

This geometry is fed into the FEA plugin and analyzed based on the direction and magnitude of the load, the resolution and desired number of iterations. The output data from the FEA plugin consists of the most stressed points within the boundary volume and their corresponding stress values.

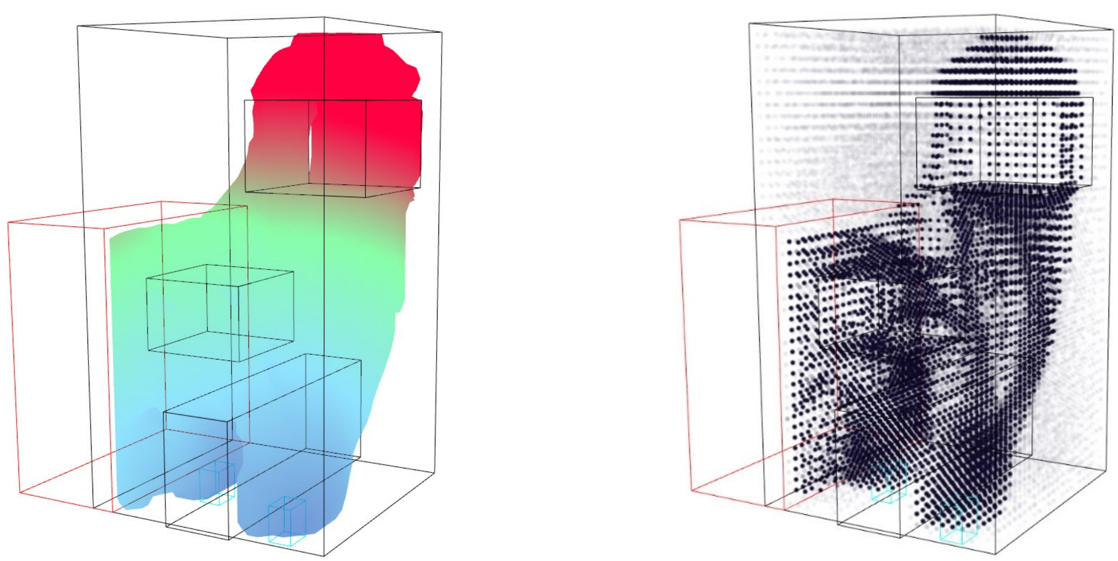


Illustration 47 Visualization of structural deflection and stress points

This data is further refined by using a shortest walk algorithm to find the shortest path from supports to loads, through the field of points.

9.3 Shortest Walk

The shortest walk algorithm is used to find the shortest path through an interconnected curve network built from the stress point cloud output from the FEA. The shortest path represents the path of least resistance from load to support that a force travels through. By interpolating the data the structure can be refined to a greater degree without the lengthy computation time required for a very high resolution FEA.

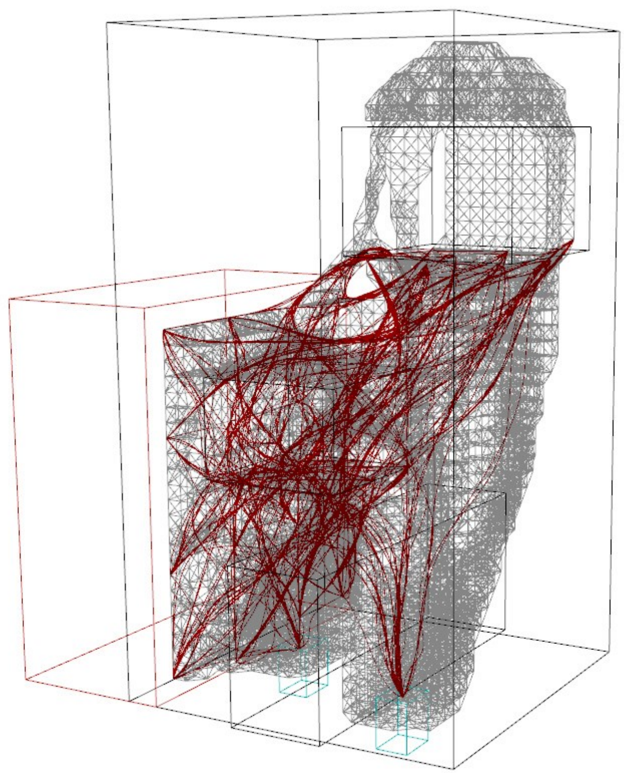


Illustration 48 Shortest walk through network of stress points

The shortest walk is built on a line-based topology calculator that uses the A* search algorithm (also known as A Star). A* uses a best-first search and finds a least-cost path, the shortest distance, from a given initial node to one goal node (out of one or more possible goals). As A* traverses the graph, it follows a path of the lowest expected distance, keeping a sorted priority queue of alternate path segments along the way (Hart, Nilsson, and Raphael).

The output produces bundled curves much like Frei Otto's wool thread experiments, previously shown in Chapter 4, which were used to calculate the shape and patterns of movement. Similarly, it is a directional systems that economizes on the number and direction of paths; merging and bifurcating to maximize the stress distributed within the structure.

9.4 Mesh Generation

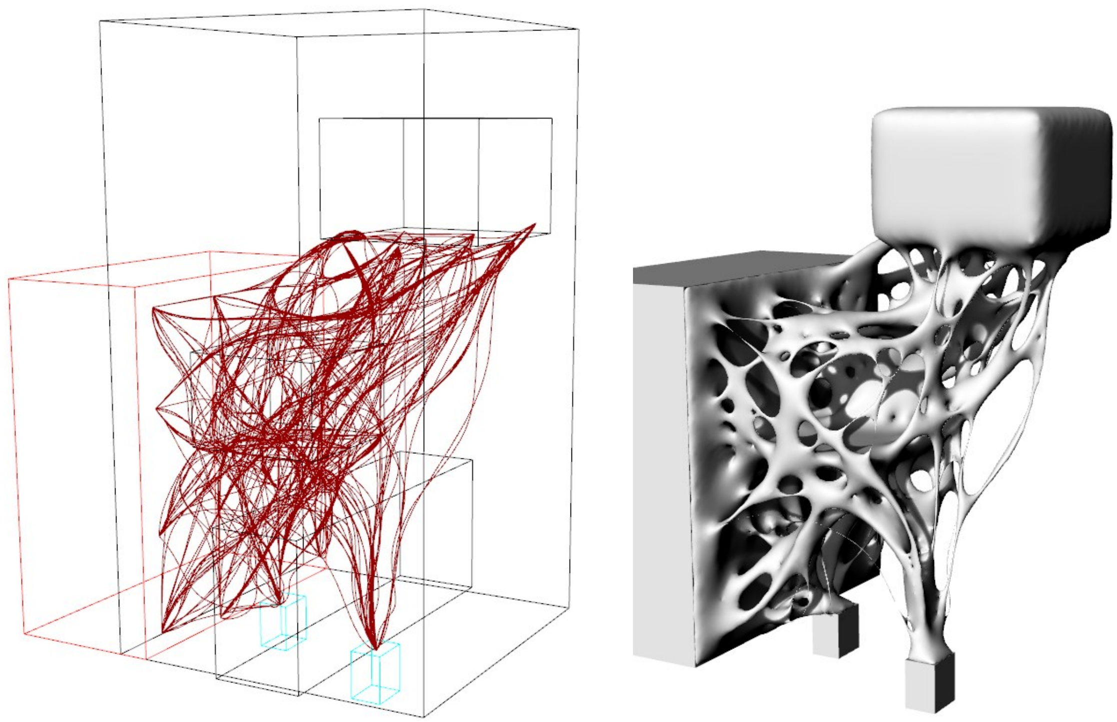


Illustration 49 Shortest walk curves and resulting mesh

The output curves can subsequently have their curvature manipulated or simplified for aesthetic purposes. The curves then get wrapped in a thickened mesh to create the final form. The denser the grouping of curves the thicker the mesh, resulting in node structures much like heavily mineralized trabeculae or a reinforced gusset.

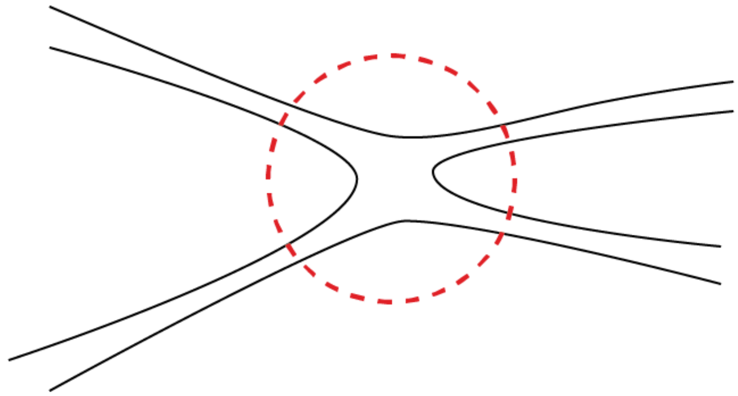


Illustration 50 Diagram of thickened mesh node

The mesh is generated used the Marching Cubes method outlined in the following section.

9.4.1 Marching Cubes

Marching Cubes is an algorithm developed for rendering isosurfaces[8] in volumetric data. It is based on the idea that we can define a voxel (cube) by the values of the points at the eight corners of this cube. If one or more points of a cube have values greater than the specified isovalue value, the cut-off value, we know the point must be within the isosurface. By determining which edges of the cube are within the isosurface, we can create triangular patches which divide the cube into regions inside and outside of the isosurface. The patches from all cubes on the isosurface boundary are joined to create a surface representation (Lorenson and Cline). This technique is often used to reconstruct data from CT and MR scans.

[8] An isosurface is a surface that represents regions of a particular value (density, temperature, etc) within a volume of space, often used to visualize datasets.

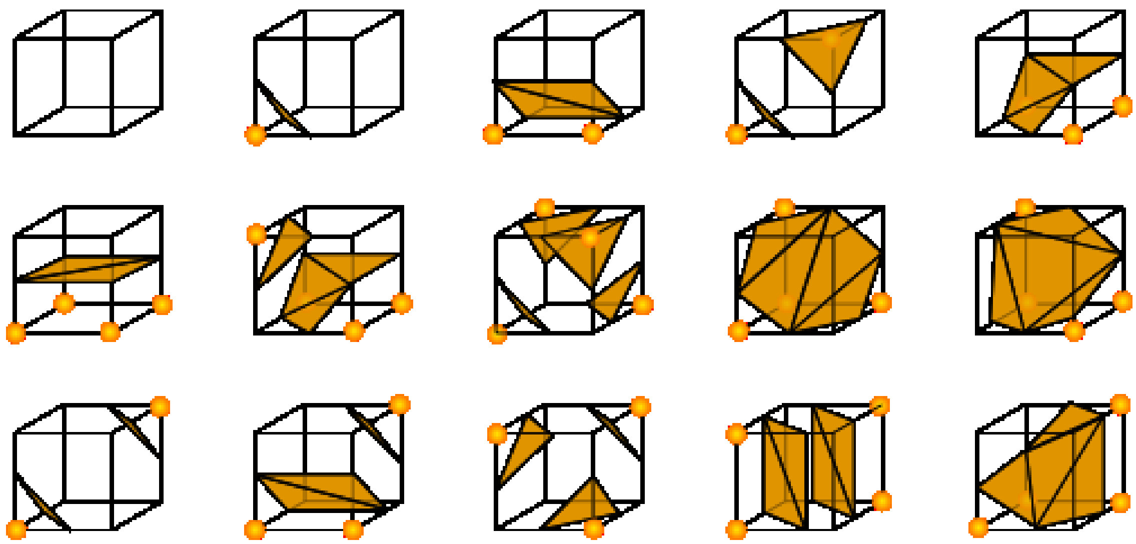


Illustration 51 The 15 configurations for any voxel. Vertices with a dot are within the isosurface (Lorenson and Cline)

9.5 Notes on Loading

Based on experimenting with this algorithm it has become apparent that it is beneficial to exaggerate the anticipated loads. The designs produced are digital prototypes and not finished structures, so the true forces involved are unknown variables. Increasing the magnitude of the loads helps to compensate for variability in live loads. This not only strengthens and rigidifies the structure but it generates the tendency to develop finer structural elements.

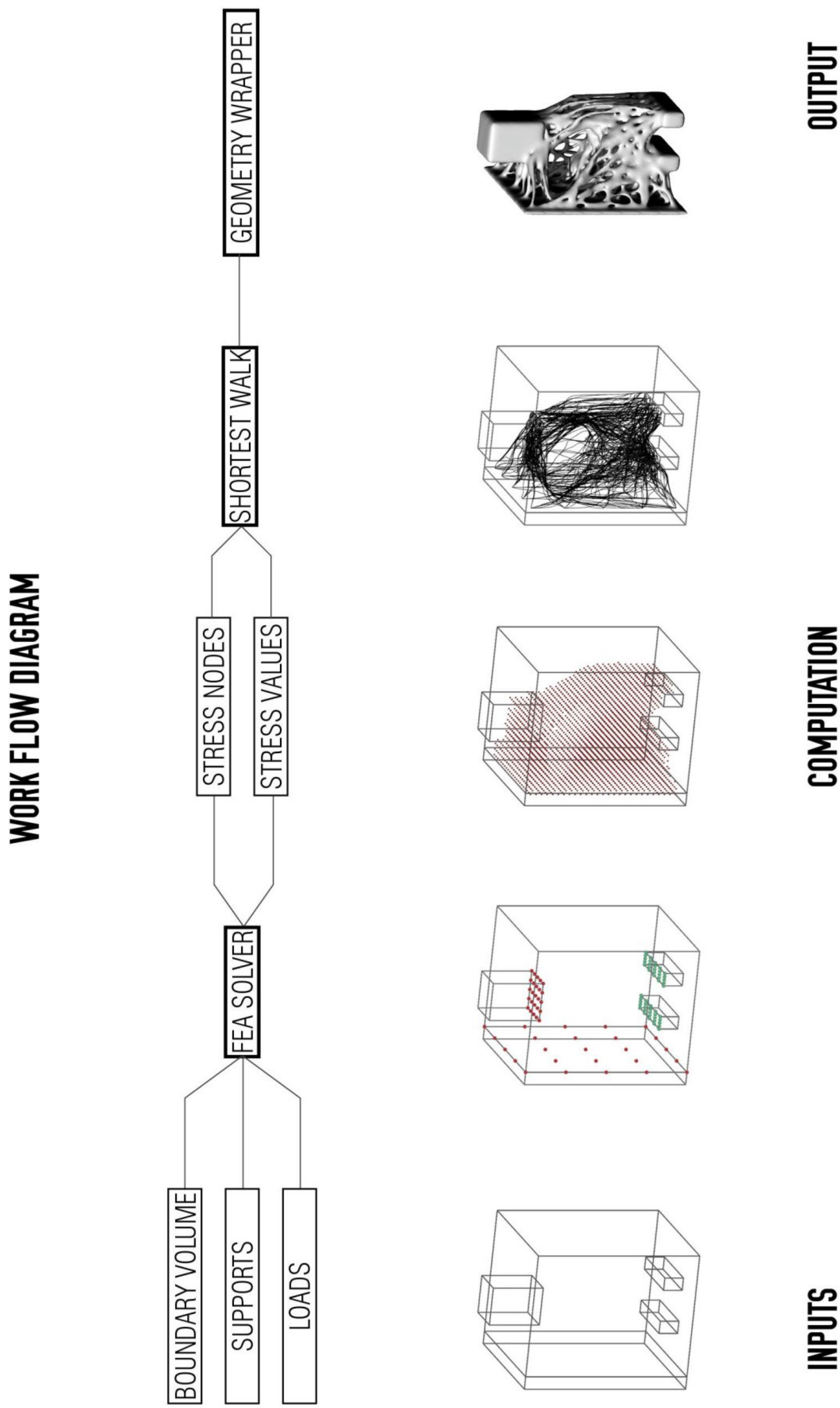


Illustration 52 Work flow diagram

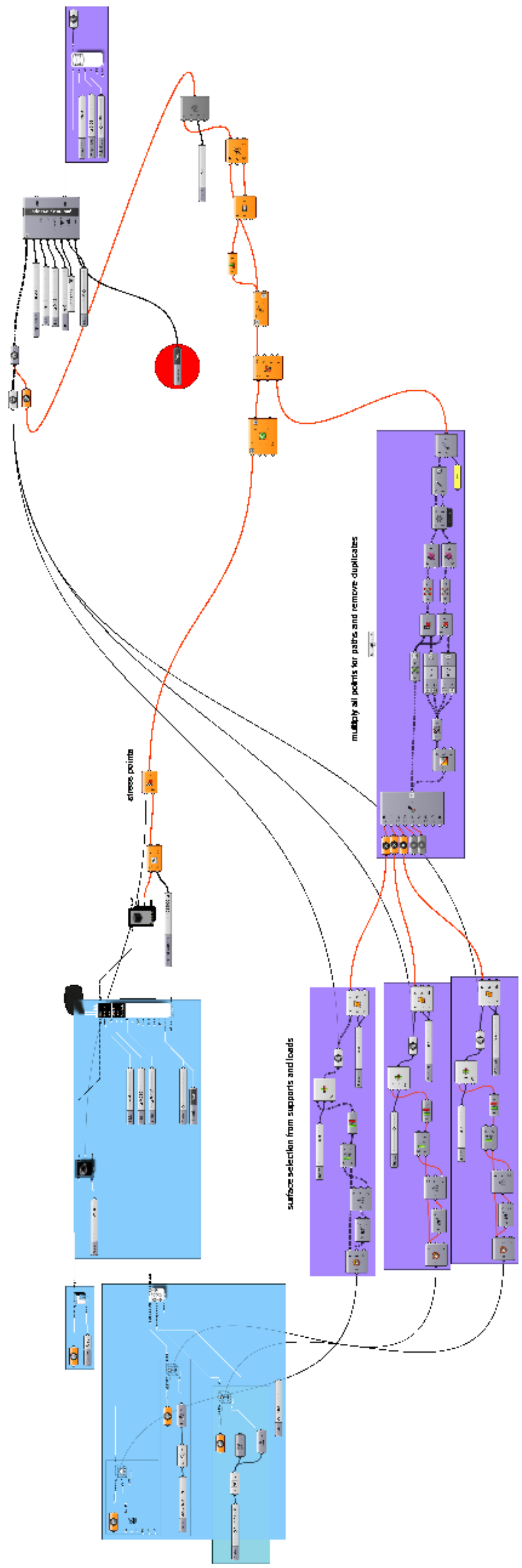


Illustration 53 Grasshopper script used to generate all structures

10 Chapter: Architectural Design

10.1 Human Forces

How can we begin to introduce additional ‘forces’ into the development of architectural structures using these methodologies? We have already demonstrated the feasibility of dealing with external environmental forces, but this does not address programmatic or human ‘forces’. The structure needs to stand under basic loading conditions but it also needs to accommodate human activity and other necessities. The resulting structures are a hybrid of architecture and engineering because they respond to the needs of architectural programming and aesthetics as well as the need for optimization. The techniques developed with the design methodology outlined in chapter 9 can be applied in any situation involving forces and functions; at all scales of construction, from furniture to skyscrapers.

10.2 Case Study: Furniture

The following models are created using the previously outlined design techniques as a means of optimizing furniture in order to withstand the necessary loading conditions as well as meet the requirements for human use and interaction.

10.2.1 Table

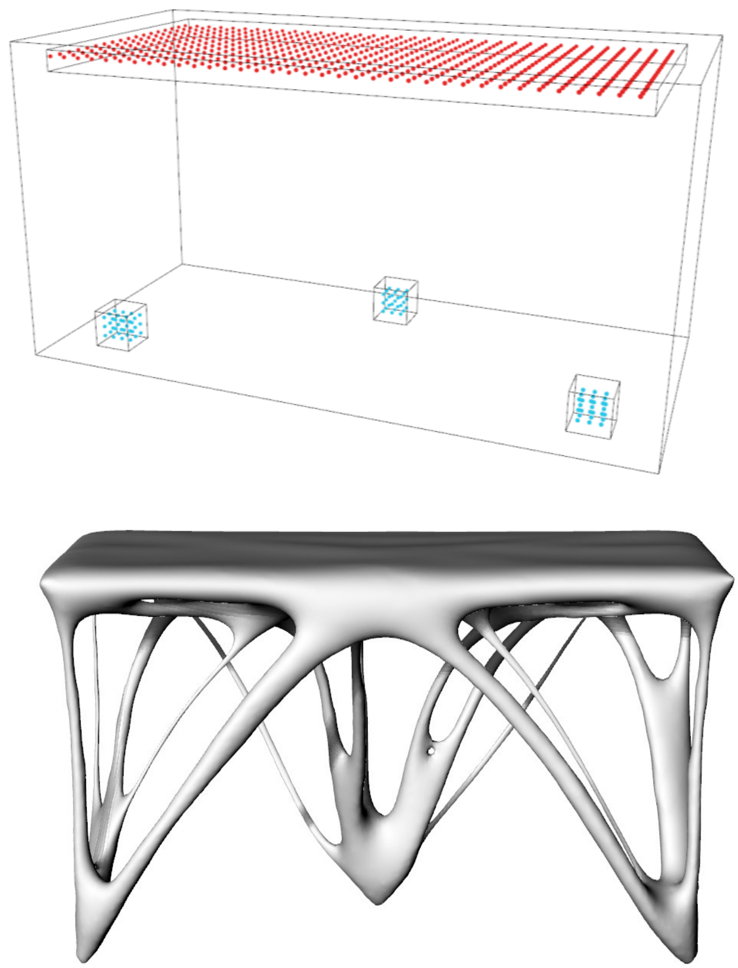


Illustration 54 Loading diagram and rendering of an optimized table

A table is a basic example of an optimizable design. It requires a stable flat surface and space below to accommodate seating. The table top is created by subjecting the design space to a uniform load using three feet for support. This was designed as a desk for a single, seated user and takes into account the need to support gravitational, self-weight forces along with the imposed uniform distributed load. The load is exaggerated to accommodate stresses during use. The expressive qualities of the structure emerge as a reaction to the placement and number of supports desired.

10.2.2 Stool

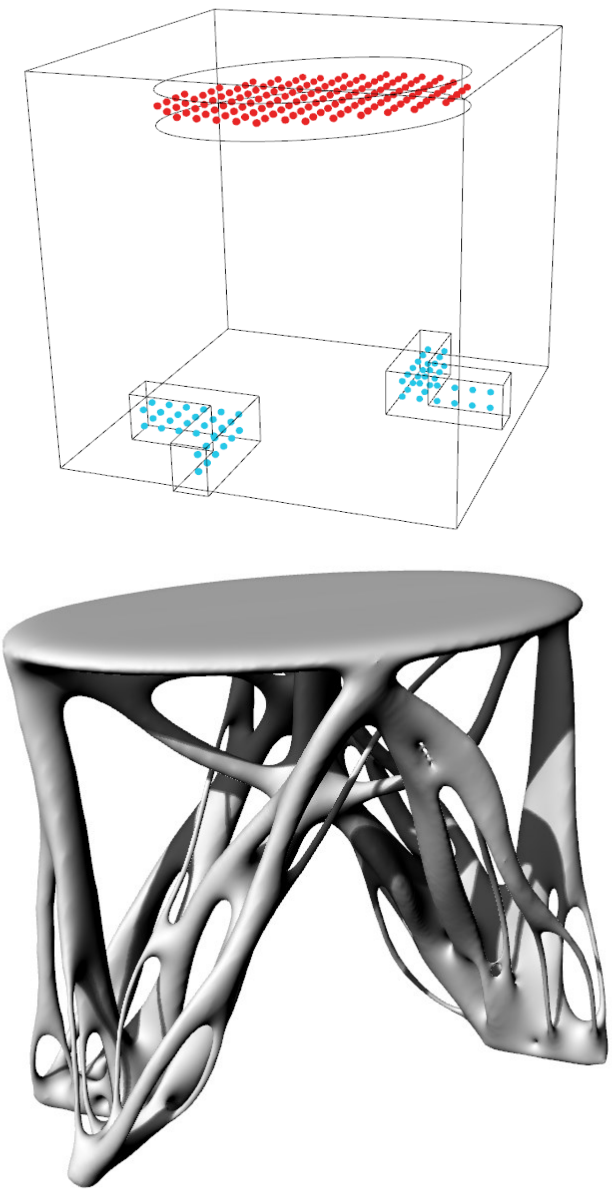


Illustration 55 Loading diagram and rendering of an optimized stool

A stool, like a table is also subject to a flat uniform load. The central space below the seat remains empty to allow for the placement of feet underneath. The design develops a complex cross-bracing structure to resist the outward push on the supports of the stool as it is subjected to a load.

10.2.3 Chaise Lounge

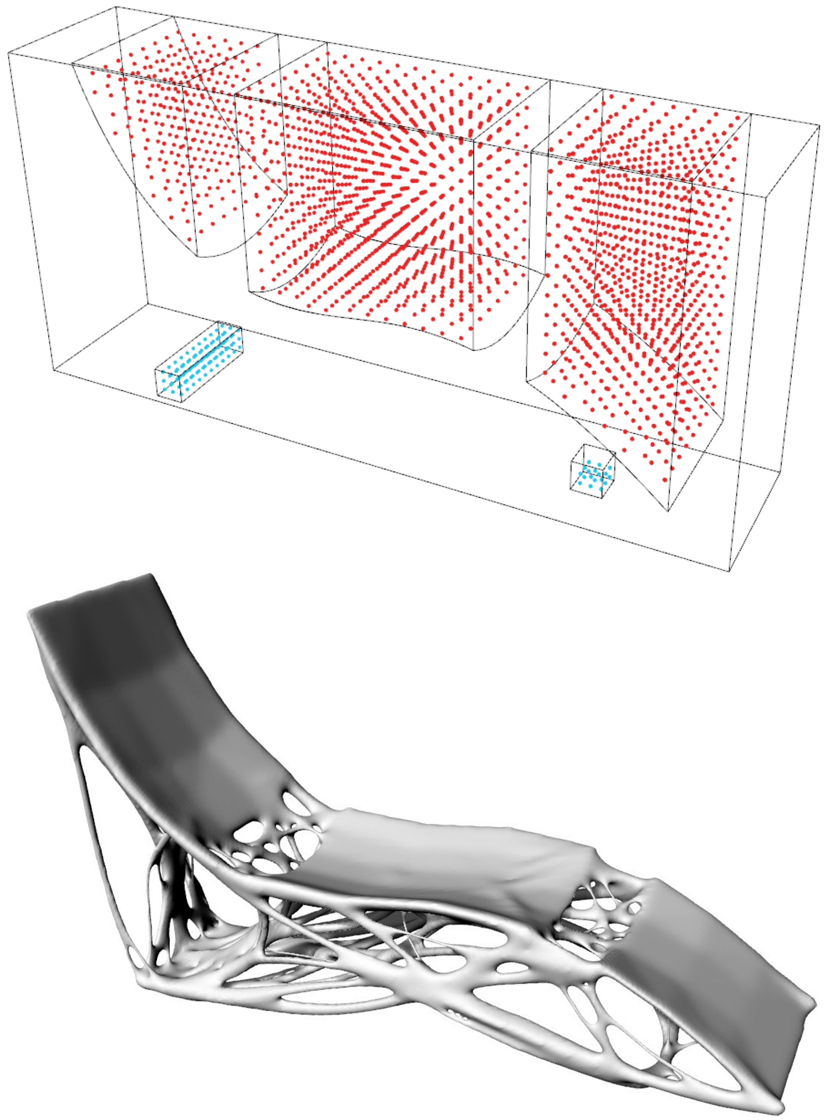


Illustration 56 Loading diagram and rendering of an optimized chaise lounge

A chaise has a multipart loading setup that corresponds to both the downward and backward direction of the load; accommodating for the lean of the body as well as the gravitational force. The chair is supported by a long strip at the back and a point at the front near the feet. The force applied is of the same magnitude as the stool.

10.3 Architectural Design

We will now look more specifically at the application of these design techniques regarding architectural criteria and functions.

10.3.1 Case Study: Spiral Staircase

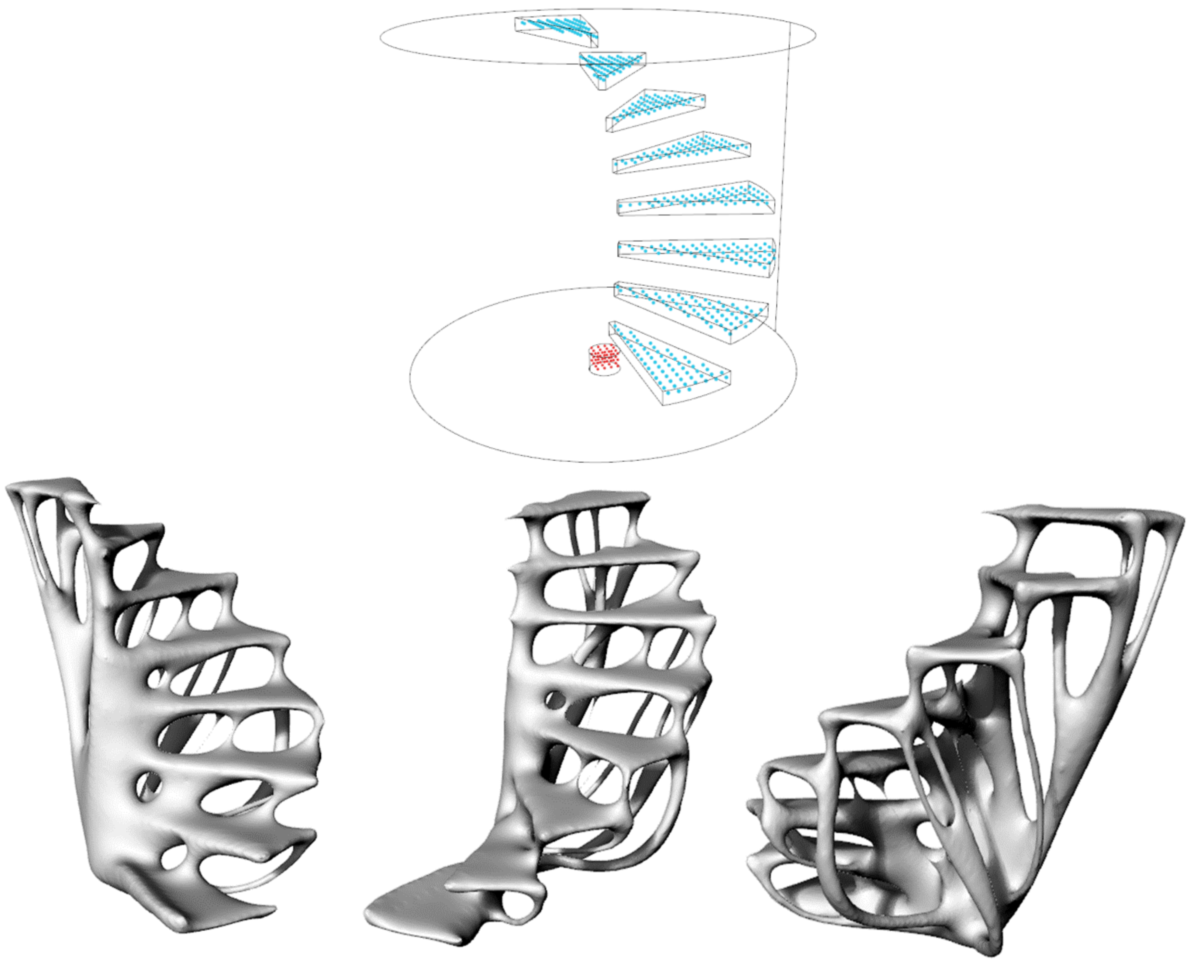


Illustration 57 Loading diagram and rendering of an optimized spiral staircase

A stair was developed using a single support point at the base with eight loaded steps rotating around and rising above the support. In the design boundary the area above the steps is designated as an empty void and kept clear for circulation; forcing all of the structure to be placed below. The structure branches out to support the edges of the steps and responds accordingly as it rises by reducing material where less structure is required.

10.3.2 Case Study: Bridge

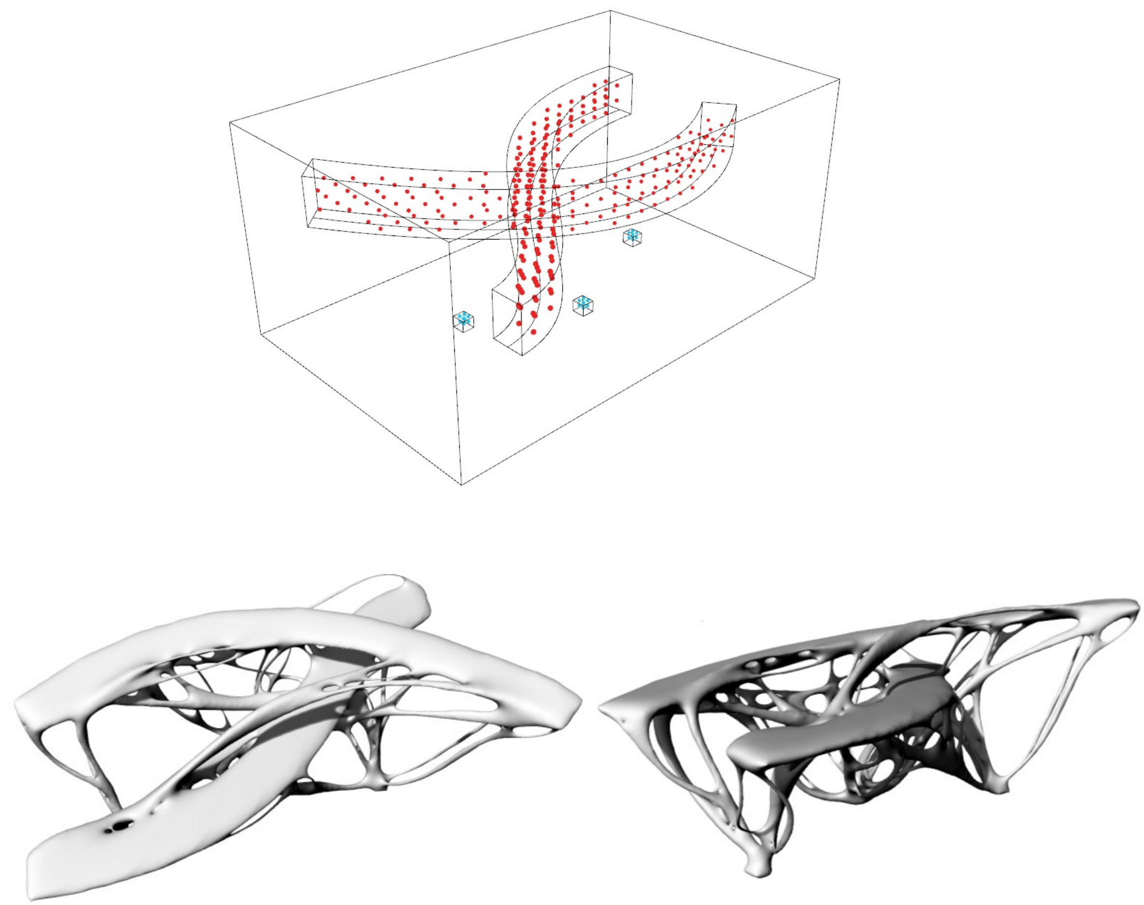


Illustration 58 Loading diagram and rendering of overlapping bridges

A section of a bridge was developed by balancing two overlapping paths from three small, staggered support points; the result is an intricately intertwining structure. Space for circulation on the paths is left clear and structure grows around these voids. This particular scenario exemplifies the algorithm's strength in resolving complex cantilevered structures with an economy of materials.

10.3.3 Case Study: Pavilion Design

With something at the scale of a pavilion it is feasible to construct and fabricate a structure using entirely digital methods. Architect Achim Menges specializes in this digital fabrication at this scale, mixing generative process and novel fabrication techniques to construct pavilions. This design scenario demonstrates the use of the generative algorithm in producing and entire pavilion structure. This design scenario demonstrates the use of the generative algorithm in producing and entire pavilion structure that features an undulating roof supported at points.

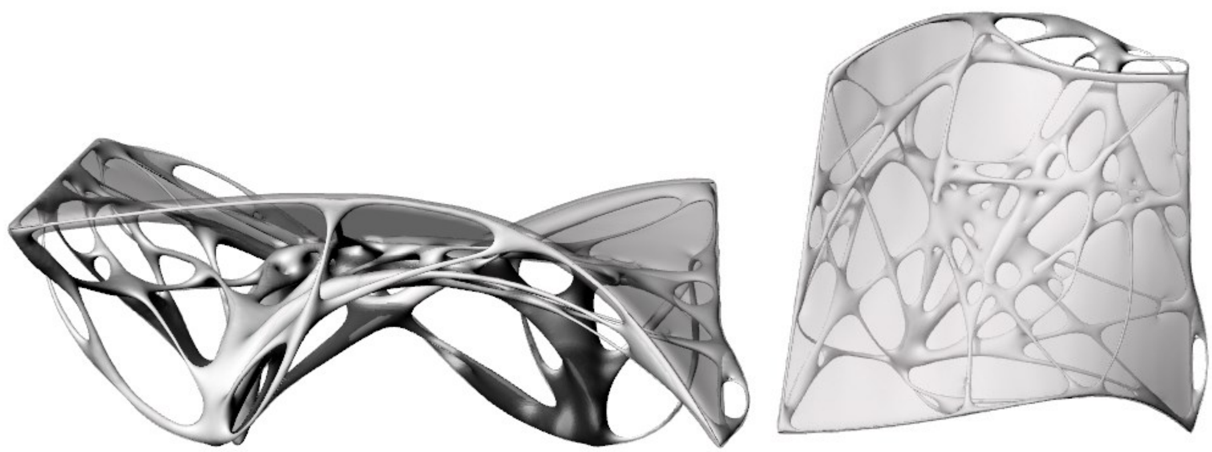


Illustration 59 Side and top view of a pavilion sized structure supporting a curved roof

At this scale a structure could be CNC milled, or potentially even 3D printed. The benefit of designing at the scale of a pavilion is that there is no need to address more complicated architectural issues like vertical circulation and building envelope.

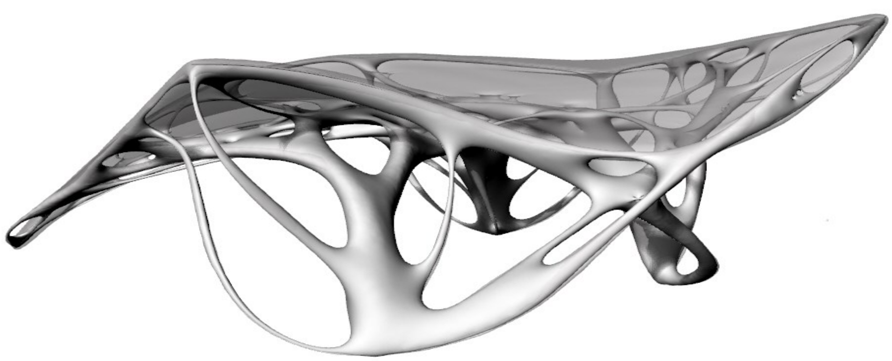


Illustration 60 Perspective view of pavilion

10.4 Detailing

By taking advantage of the capabilities of large scale additive manufacturing, as discussed in Chapter 8, this method of design optimization can also be applied at smaller scales.

10.4.1 Case Study: Facade Detail Design

At building scales beyond pavilions we are relegated to fabricating portions of a building's skeleton or façade elements. The benefit of mixing traditional architecture with digital elements is that there is no need for use of traditional construction modules because each component can be manufactured uniquely.

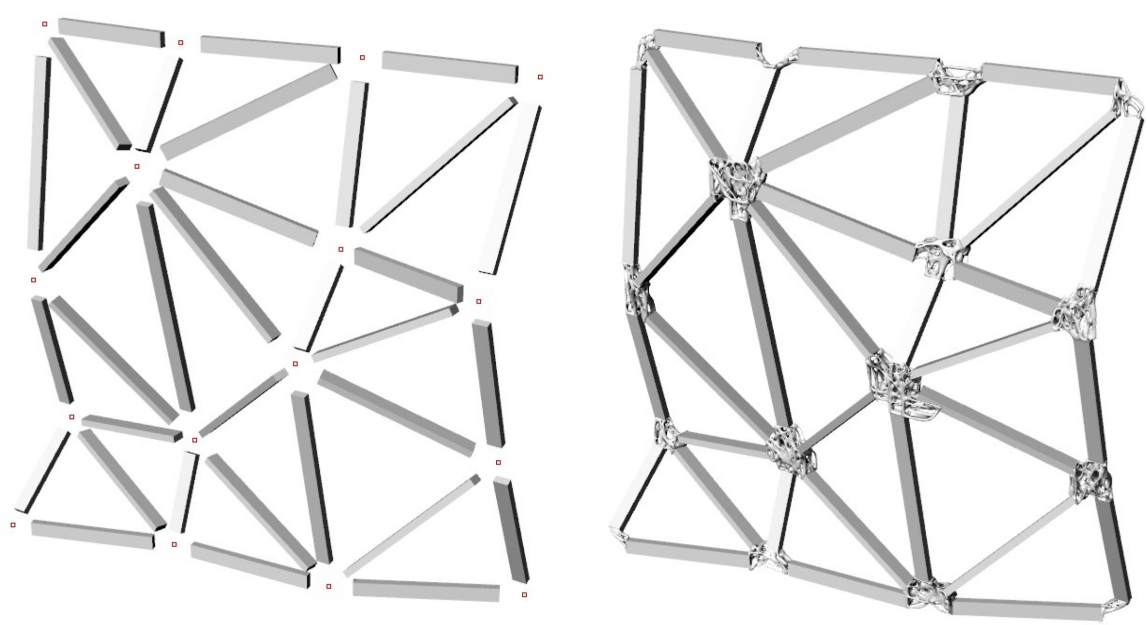


Illustration 61 Generation of unique connective components for a faceted façade

This design scenario shows the use of generative design for joint detailing on a folded façade. The structural elements are all identical in shape and size but due to the folding shape they each connect in completely different ways. To address this each connection is treated as a unique design condition.

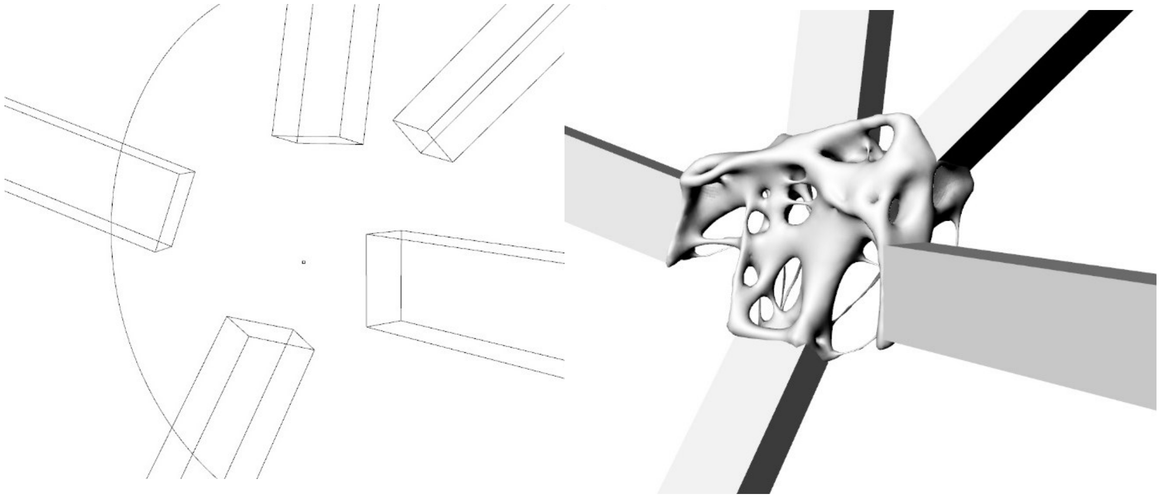


Illustration 62 Close-up view of the generatively produced connective component

At the detail scale these connective elements could easily be 3D printed in structural steel, much like the nodes designed by Arup.

10.4.2 Case Study: Infill Optimization

Another example, the space within a floor slab can be optimized using a voronoi algorithm to create a strong yet lightweight infill which simultaneously provides the opportunity to seamlessly integrate ductwork, plumbing, and electrical in the structure.

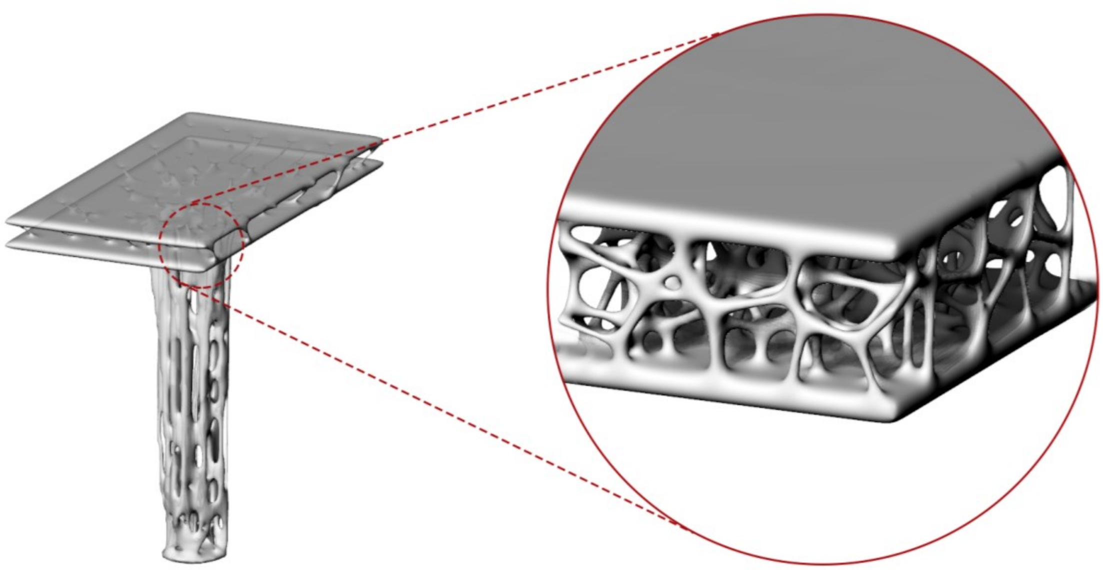


Illustration 63 Optimized floor slab infill

11 Chapter: Implications and Conclusions

> "Yes, there is more to the future than printing buildings or growing chairs. Rather, the future lies in questioning what an inhabitable structure is. When we consider printing concrete with variable density as in bones, we do not mean to do this simply to reproduce the same old buildings… In other words, the aim of printing buildings is not a matter of redoing what has already been done, but rather of reconceiving the creation of form for buildings." - Neri Oxman (*Printing 3D Buildings*, whatsnext.blogs.cnn.com)

11.1 Digital Computation

The use of the computer in architectural design is not a new thing, but the use of the computer as part of the design process rather than a drafting tool is. Engineering and analysis that was once relegated to post-design optimization is now integral to the design process. The role of the architect is shifting from form maker to manipulator and guider of the generative process where the designer defines the constraints and runs the program. This is not a diminished role requiring less skill or imagination, instead an imaginative use of digital tools and generative processes is needed to intelligently and creatively guide the stochastic design process.

> "It is programs such as this that reveal the true potential of the digital realm in influencing the process of design itself, by opening up fields of possibilities. The computer, then, emerges not only as a prosthetic device that extends the range of the architectural imagination, but also – much like a calculator – as a tool of optimization that offers a more rigorous means of searching out possible options than what could be described as the pseudo-computational logic that often dominates contemporary practice." (Leach, 36)

11.2 The Problem with Optimization

Computer based optimization is a powerful tool for finding the 'best' solution but requires the designer to understand what the best solution really is (with respect to computing). What exactly is being optimized? In the case of the software used in the development of designs for this thesis it is the stiffness and lightness of the structure – its ability to resist a maximum amount of deflection with the minimum amount of required material. But this does nothing in terms of optimizing architectural function or aesthetics.

A problem and limitation of optimization is that it requires reducing the situation to a set of data which can be simulated by the computer. No matter how thorough the data, it can never replicate the complete complexity of a natural environment. Precision is needed in the initial setup of the design scenario; the stresses should be accurately anticipated as the final output is optimal only for the prescribed conditions. Another issue is that of material; while topology optimization software can determine the optimal shape it cannot determine the optimal material to use for that shape.

There is a certain faith required in constructing biomimetic structures, constructing something that looks like the original and hoping it performs in the same way when translating of form, scale, and material into buildable architecture. By copying the process rather than appearance using new digital analytical and predictive tools, as well as cutting edge production techniques, we can remove much of the guess work.

11.3 Intuition and Imagination in Optimization

Optimization software has the potential to function beyond intuition and reveal potential structural problems or solutions that may have otherwise been unnoticed. This is especially true in situations where the loading conditions are complex or unusual; solutions are often unpredictable and non-repetitive.

Software still offers the potential for imagination, it is easy to assume that using generative design requires little input from designers but the algorithms that generate the designs need to be written. Defining the constraints for a generative system is itself an avenue for expression and imagination. The relationship between stress and structure is a dialogue which the designer can manipulate for non-optimal (architectural) goals.

In architecture, form never constitutes only the optimal structural shape it also embodies and integrates numerous other factors; it must also encompass complex organizational and functional requirements along with aesthetics. Within the system we can identify areas that can be altered without affecting the integrity of the structure; they can be modified to adapt to the architect's spatial and programmatic requirements. The structure then develops from and adapts to these constraints. In this design process, external force is just one design aspect of many and is no longer the only defining factor for the structure. Developing a structure for purely optimal goals remains in the realm of engineering.

11.4 Implications of Bone Generated Structures

Optimization and generative algorithms offer a new area of exploration in architecture and, when paired with construction-scale 3D printing, has the potential for a massive shift in the process of design to fabrication. But we must still create a design that understands the consequences and realities of building. The biggest issue comes with fabricating such complex structures. It is unfeasible and uneconomical to do so using conventional construction techniques because it lacks repetitive shapes and standardized sizes.

> "The far reaching potential of computer-aided manufacturing (CAM) technologies is evident once they turn into one of the defining factors of a design approach seeking the emergence of form generation and materialisation processes." (Hensel and Menges, 2008, 57)

The previously examined additive manufacturing techniques have demonstrated the ability to fabricate these structures with few constraints and the construction of complex bone generated structures is certainly within the realm of possibility. As stated by Menges and Hensel the increased integration of these manufacturing techniques will begin to define new approaches to design.

In developing bone generated structures it becomes apparent that the distinctions between wall, column, and slab begin to disappear. Instead their distinction is attributed primarily to the variations in material distribution that is produced by the magnitude and direction of environmental forces. The structures no longer adhere to typical architectural typologies; rather they result from analysis and algorithm. This recalls the development of graphic statics, where the teaching of structures was no longer based solely on precedent buildings and examples, but instead on theories and analytical methods.

Inhabitation of these complex spaces is another thing to consider. We can build nearly any shape imaginable, but floors still need to be flat and basic functions and services need to be integrated. Another issue in using these algorithms in large scale construction beyond manufacturing is their unpredictability. The placement of structural elements can be suggested but cannot be entirely predicted making logical floor plan layouts difficult.

By considering each structure as an individual form resulting from its environment, we begin to move away from the view that a building is simply a variant of an established type. The use of generative systems in architecture erodes the predefined typologies in favour of emergent and environmentally responsive structures.

11.5 Manufacturing Generative Architecture

The difficulty with constructing architecture based on generative processes is that the forms are defined by response to environmental factors. The features that make this kind of generative architecture so interesting are also what make it so difficult to manufacture. While typically in architecture form is defined mainly by the capacities of technical production. We are now at the point where the ability to construct forms matches the ability to design it. The complex and irregular forms of generative design can only be constructed using digital fabrication techniques.

The unfortunate part about digital fabrication is that the cost of manufacturing is potentially very high. This is evident in 3D printing even at a model making scale where plastic costs $2 to $5 per cubic centimeter and ranges $8 to $20 per cubic centimeter for metals. However, the concrete printer D-Shape claims to be 30 to 50% less expensive than traditional methods and 4x faster than traditional construction.

In the case of the design work of this thesis the algorithm developed serves to generate structural forms in a non-deterministic method using the generative process of bone remodeling. The designer establishes the system’s constraints and then executes the program, which resolves the structure into a particular configuration. Each configuration is a unique structural form that will support itself against gravity and the prescribed loadings. The resulting structures cannot be constructed by any traditional means. Generative processes like this reveal the potential of the digital in influencing the design process.

11.6 Conclusions

Bone is the perfect example of analysis and formation run in parallel and produces a remarkable new paradigm for architectural design. By utilizing bone remodeling algorithms as an optimization tool it offers the possibility for designing highly efficient and expressive structures formed by forces of gravity, environment, and architectural function. That being said, its purpose is more as a pre-design tool than one that outputs a complete and finished form. By beginning with an integrated design that is formed by the forces imposed on it, it avoids having to post-engineering a complex structure and shoe-horn it into a form in order for it to stand.

The preceding sections have presented the generative mechanisms that govern the formation of bones and applied them to digital modelling scenarios. From these analyses it becomes clear that when the processes of modeling, analysis and manufacturing are unified with a digital method that simulates morphogenesis design can actually begin to approach the abilities of nature. I'm certain the time will come when buildings will be constructed in a manner comparable to bones.

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