(IN)FORMING MATERIAL
The Generative Potential of Plywood

By

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Abstract

"We are beginning to recover a certain philosophical respect for inherent morphogenetic potential of all materials. And we may now be in a position to think about the origin of form and structure, not as something imposed from the outside on an inert matter, not as a hierarchical command from above as in assembly line, but as something from that we tease out of those materials as we allow them to have their say in the structures we create"

Manuel DeLanda 2004

This thesis aims to contribute to the development of design and construction methodologies through the integration of material-based design strategies and digital fabrication. The explorations conducted as part of this research concurrently pursue the development of an integrated design approach, one in which material, form, structure and space making are inherently linked.

The research contained herein explores the specific material behaviours associated with plywood and attempts to advance these findings using both traditional and modern fabrication techniques. The thesis will address the following questions:

- a) Can the material properties of plywood be employed as more than a sheathing material?; *and*
- b) Is it possible to unlock the material potential towards creating an active lightweight structural system?

This paper presents research surrounding the material properties of plywood followed by a series of material explorations. These findings are then implemented into a proposal for a final lightweight structural system. In this way, such research can contribute to the growing field of material-based design, enabled by digital tools and inspired by natural processes.

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Table of Contents

Abstract.....	ii
Acknowledgements	iii
Table of Contents	iv
List of Illustrations.....	vi
Introduction.....	xv
1 Chapter: Theories on/of Materiality	1
1.1 Material and Form: A Separation in Architectural Practice	1
1.2 Industrial Revolution (Material in the West).....	4
1.3 Digital Revolution (Computer-Aided Design in the Digital Age).....	5
1.4 Material Design	8
1.5 The Parts and the Whole (Mechanistic vs. Systemic)	11
1.6 How We Build: The Parts and the Whole - Precedent Case Studies	15
2 Chapter: WOOD AS A MATERIAL.....	29
2.1 Why Wood?.....	30
2.2 The Complex Material Behaviours and Characteristics of Wood	34
2.3 Plywood and Veneer.....	40
2.3.1 Production of Plywood.....	41
2.3.2 Plywood Precedents	47
3 Chapter: Material Experimentation and Implementation	54
3.1 Background Research (Hub Ottawa – Resonant Project).....	54
3.2 Material Investigation.....	62
3.2.1 Structural Experiments.....	62
3.2.2 Skin Explorations	67
4 Chapter: Proposed System.....	79

4.1	The Development of the Proposed System.....	79
4.1.1	Prototype for an Active Bending Lattice (Structure Prototype #2).....	79
4.1.2	Scaled Skin (Prototype #2).....	84
4.1.3	1:5 The System as a Whole.....	88
4.1.4	System Structural Properties	97
4.2	The Development of the 1:1 System:	102
4.3	Structural Details	112
4.3.1	Proposed Actuation Spacer Units.....	112
4.3.2	Connection Details	116
4.4	Lessons Learned and Future Considerations	128
	Conclusion	131
	Bibliography or References.....	134

List of Illustrations

Illustration 1 Centre Pompidou in Metz, 2010 (http://old.designboom.com/cms/images/fiona/metz005.jpg).	16
Illustration 2 The “Multihalle” Mannheim, 1975 (http://www.smdarq.net/case-study-mannheim-multihalle/)	16
Illustration 3 Left: The Centre Pompidou’s structural roof mesh. Right: The Chinese straw hat that inspired the roof structure (http://www.architects24.com/project/centre-pompidou-metz/overview/938/index.html)	17
Illustration 4 Top: A Kagome lattice pattern projected onto the free-form surface of the roof. Bottom: The digital model of the roof structure for the Centre Pompidou. (Top: Oxman, 93. Bottom: http://old.designboom.com/weblog/cat/9/view/10071/shigeru-ban-centre-pompidou-metz-opens-may-12.html).	18
Illustration 5 The structural composition of the roof system, comprised of 3 double layer wood laths with rectangular cross sections (http://cwmags.com/cw-1-7/basic/page22.php)	19
Illustration 6 Illustration 6 The various categories used in the fabrication of the roof segments (http://gradstudio2014.blogspot.ca/2014/02/gbc-centre-for-innovation-in-wood.html)	20
Illustration 7 Left: The (CNC) machine milling off portions of timber canopy members Right: Milled timber members (http://gradstudio2014.blogspot.ca/2014/02/gbc-centre-for-innovation-in-wood.html)	20
Illustration 8 The construction of the roof assembly of the Centre Pompidou, Metz (http://cwmags.com/cw-1-7/basic/page21.php)	20
Illustration 9 The “Multihalle” Mannheim, 1975 (Interior space) (http://commons.wikimedia.org/wiki/File:Multihalle07.jpg)	21
Illustration 10 The hanging chain model used in the design of the Multihalle (http://www.smdarq.net/case-study-mannheim-multihalle/)	22

Illustration 11 The flat assembly of the lattice diagrid structure of the Multihalle (http://www.smdarq.net/case-study-mannheim-multihalle/)	24
Illustration 12 Multihalle's joint connection detail (http://shells.princeton.edu/Mann1.html).....	24
Illustration 13 The lattice distortion of the Multihalle's diagrid structure (http://shells.princeton.edu/Mann1.html)	25
Illustration 14 From flat to curved: The forces acting along the edges of the assembly cause the wooden laths to bend into a curved form (http://shells.princeton.edu/Mann1.html).....	25
Illustration 15 Workers tightening the system connections of the Multihalle (http://www.smdarq.net/case-study-mannheim-multihalle/)	26
Illustration 16 A diagram illustrating the Multihalle's system assembly via a steel cable brace (http://shells.princeton.edu/Mann1.html)	26
Illustration 17 The Multihalle's substructure connection detail (http://shells.princeton.edu/Mann1.html).....	27
Illustration 18 Scanning electron micrograph of wood from a Siberian pine tree illustrating the internal biological tissue and structure of wood (Michael and Menges, 37).	29
Illustration 19 The three principal axes of wood with respect to grain direction and growth rings (http://www.ggi-myanmar.com/wood/).....	31
Illustration 20 The Boardman Tree Farm plantations. Top: Satellite view of the plantations. Bottom: Arial views of the plantations (http://www.gildemeister-usa.com/industrial%20image%20html%20pages/Greenwood%20tree%20farm.html) ..	33
Illustration 21 Layered cell structure of wood, illustrating the orientation of the Micro- fibrils within Contained within each layer (Mullins, 52).....	34

Illustration 22	Illustration showing the cambium layer of wood (http://halfsidebamboo.info/wordpress/wp-content/themes/thesis/images/vascular/1_cambium.jpg).....	36
Illustration 23	The composition of wood, comprised of three main substances: Hemicellulose, Cellulose and Lignin (http://venice.umwblogs.org/files/2008/12/wood-cellulose-rowell-36-001.jpg).....	37
Illustration 24	Left: The cell structure of softwood. Right: The cell structure of hardwood (http://www.boeingconsult.com/tafe/mat/Timber/HowTreeGrows-OH.htm)	37
Illustration 25	Diagram illustrating the cell structure of vessel elements and tracheids (http://bio1151.nicerweb.net/Locked/media/ch35/plantcells_xylem.html)	38
Illustration 26	Plywood's cross laminated construction assembly. The arrows indicate the grain direction of the veneer sheets (http://justpaint.org/jp29/jp29/understanding-wood-supports-for-art-5.jpg)	41
Illustration 27	The production process of veneer and plywood (http://www.wisaplywood.com/en/plywood-and-veneer/veneer/veneer-production-process/Pages/default.aspx)	42
Illustration 28	A debarking Machine (Mullins, 336)	43
Illustration 29	A rotary lathe, used in the manufacturing of veneer sheets (Left: Mullins, 249. Right: http://classicwoodworkinginc.com/InfoData_Pop/VeneersCut.html)	44
Illustration 30	A hot press machine, used in the lamination process of plywood (Mullins, 251)	45
Illustration 31	The images above depict the Model No. 41 lounge chair and the Model No.31 cantilever laminated wood chair, designed by Alvar Aalto. (http://hfoc.wordpress.com/2011/05/31/cult-classics-the-pioneer-of-scandinavian-design-alvar-aalto/)	49

Illustration 32 Left: Eames Splint for the U.S. Navy, 1942. Right: Eames DCW side chair, 1946 (Left: http://www.oeditorial.com/pt-pt/eames-leg-splint/ Right: http://www.metmuseum.org/toah/hd/eame/hd_eame.htm).....	49
Illustration 33 Top: Aggregated Lamination process used during the construction of the ICD/ITKE Research Pavilion in Stuttgart. Bottom: Images of the overall ICD/ITKE Research Pavilion 2010 (http://www.achimmenges.net/?p=4443).....	53
Illustration 34 Radical Wood Pavilion (http://eerolunden.com/2012/12/18/radical-wood-pavilion/).....	53
Illustration 35 Resonant Currents project: A preliminary installation located at Carleton University.....	56
Illustration 36 Double strip unit used in the design and fabrication of the Resonant Currents project. Illustration depicts the sequence of assembly	57
Illustration 37 A single double strip unit	58
Illustration 38 A multiple unit assembly.....	58
Illustration 39 Connection detail used to fasten units to one another	59
Illustration 40 The developed and finalized formation of the installation.....	59
Illustration 41 The Hub Ottawa space showcasing the finished installation from the Resonant Currents project.....	61
Illustration 42 A simple physical test in which two forces act on a single (3-Ply) plywood strip	62
Illustration 43 The self-organizing formations of plywood when responding to applied forces.....	63

Illustration 44	Structural prototype #1: active plywood truss component	64
Illustration 45	The bending behaviours of an active plywood truss component	66
Illustration 46	Illustration of the breaking point of the system web (establishing the system's maximum bending strength)	66
Illustration 47	Workers applying the skin of the Multihalle (http://www.proholz.at/zuschnitt/19/auf-den-kopf-gestellt/)	67
Illustration 48	Scale Anatomy as found in biological examples: (Left) fish & shark (Middle) reptiles (Top Right) Plants & trees (Right Middle) mammals (Right Bottom) Insects: butterfly.....	68
Illustration 49	The development of a single stylized scale prototype, inspired by shark scales (Left: Drawn by Author. Right: http://australianmuseum.net.au/Placoid-scales/).....	70
Illustration 50	The digital model of the mold used in the lamination process of the scale prototype	70
Illustration 51	The (CNC) machine milling off portions of the mold (3/4 Stacked MDF, Hights 3").....	71
Illustration 52	The laser cutting process of the veneer sheets	72
Illustration 53	The grain fiber direction of wood veneer relative to its bending direction	73
Illustration 54	The lamination process and its necessary tools and parts: vacuum press, mold and veneer cutouts	73
Illustration 55	Applying adhesive onto the veneer cutouts.....	74

Illustration 56	The glued veneer cutouts, ready to be laminated together against the mold	75
Illustration 57	The vacuum bag lamination process. Left: The mold is placed in the bag with the veneer sheets that are to be laminated. Right: The air is removed from the bag while the veneer sheets are pressed together against the mold in order to adopt its shape	75
Illustration 58	Investigating the malleable properties of the laminated scale.....	76
Illustration 59	A prototype model assembly comprised of several scales arranged across a substructure	77
Illustration 60	The bending behaviour of the scale and substructure assembly (Left: http://australianmuseum.net.au/Placoid-scales/ Right: Photographed by Author)..	78
Illustration 61	Top: The sine curve geometry of the lath. Middle: The two chord sections of the lath. Bottom: The overall composition of lath components	80
Illustration 62	The deformation of a lath through the adjustments of the spacer elements	81
Illustration 63	The range of motion of a lath, made possible by the adjustment of the actuating spacers	82
Illustration 64	A grid lattice composition comprised of several laths	83
Illustration 65	The scissor-like deformation of the lattice grid.....	83
Illustration 66	The “Sine” and “Cosine” scale system.....	84
Illustration 67	The fabrication process of the scales.....	85
Illustration 68	The deformation of the “Sine” scale relative to the lattice diagrid.	87

Illustration 69	The “cosine” scale’s slotted mechanism allows for the deformation of the overall lattice diagrid.	87
Illustration 70	Illustration of the 1:5 system	88
Illustration 71	Geometric deformations of the 1:5 system.....	89
Illustration 72	Further explorations of the geometric deformations made possible using the 1:5 system	90
Illustration 73	Views of the underside of system showing the transmission of light through the assembly	91
Illustration 74	The fabrication process of the large final installation	93
Illustration 75	The planar assembly of the large final installation.....	93
Illustration 76	A time lapse demonstrating the geometrical manipulation of the system whilst on the ground.....	94
Illustration 77	Illustrations of the final installation, hung at Carleton University	95
Illustration 78	Close up details of the final installation	96
Illustration 79	Diagram illustrating the compressive and tensile behaviours of structures	97
Illustration 80	Diagram illustrating the suspended system behaving in tension.....	98
Illustration 81	Diagram illustrating the system behaving in compression.....	100

Illustration 82	Antoni Gaudi's (Sagrada Familia) suspended chain models (Left: Drawn by Author. Right: Frei Otto, and Bodo Rasch 154-155).....	100
Illustration 83	Diagram illustrating the system behaving in both tension and compression	101
Illustration 84	A single Pre-stressed lath component at a 1:1 scale.....	102
Illustration 85	The lamination process of the lath component at a 1:1 scale.....	104
Illustration 86	The development of the 1:1 mold.....	105
Illustration 87	(CNC) machine cutting the veneer sheets prior to the lamination process	106
Illustration 88	Preparing the vacuum press and the mold for the lamination of a 1:1 scale	106
Illustration 89	The application of adhesive onto the veneer sheet cutouts	107
Illustration 90	Left: Placing glued veneers into the vacuum bag on top of the mold. Right: Removing the air from the vacuum tight bag	107
Illustration 91	The assembly process of the system at a 1:1 scale.....	108
Illustration 92	The completed assembly at a 1:1 scale	109
Illustration 93	The bending properties of the system illustrated at a 1:1 scale.....	111
Illustration 94	A spacer element	113
Illustration 95	Spacer element details	114

Illustration 96 Details illustrating the adjustability and range of motion of a spacer element.....	115
Illustration 97 Connection details to walls, ceilings and footings	117
Illustration 98 Connection pivot points illustrating the range of motion made possible	117
Illustration 99 3D visualization of the connections to a vertical or horizontal surface	118
Illustration 100 3D visualization of the connections anchored to footings	118
Illustration 101 3D visualization of the system and the connections anchored to walls	119
Illustration 102 A spacer cable connection	120
Illustration 103 Spacer cable connection detail	121
Illustration 104 Degrees of rotation made possible via the spacer cable connection ...	122
Illustration 105 Exploded detail of the spacer link, cable end link and the cable wall connection	123
Illustration 106 Cable connection #2	124
Illustration 107 Two scenarios in which both cable and ground connections are used to support the system.....	125
Illustration 108 Enlarged details corresponding to Ill. 100 (Detail #2: Conrad Roland 80-81)	127

Introduction

The separation between material, form, and structure in architecture is rooted in certain mechanistic design theories that are still present in the architecture profession. For many generations of architects, the importance of factors such as cost efficiency, construction speed and mass production have taken precedence over design approaches that seek to integrate material, form and structure. This thesis investigates the possibilities of integrating material-based design strategies with digital fabrication methods, by developing an integrated design approach in which material, form and structure are inherently linked.

The research looks towards the inherent material properties found in wood, more specifically plywood, and attempts to propose a design that is inclusive of this material's natural behaviours. Using traditional lamination techniques and modern fabrication methods, the thesis will also make use of digital tools to give the familiar material new life. The paper will investigate the two following major questions:

- a) Can the material of plywood be employed as more than a sheathing material?; and
- b) Is it possible to unlock this material's potential towards creating a lightweight structural system?

This paper is structured in such a way as to first offer readers a brief background concerning the traditional design methodologies which look at material, form and structure as separate entities. It then touches on the prioritization of form over material, and expands on the emergence of material-based design and its significance for the architectural field. The second portion of Chapter 1, expands on these two design approaches and illustrates how they are reflected in the theories of Holism and Reductionism. Following this, two precedents are presented in the form of case studies involving projects that feature these two contrasting methodologies in architectural design. Chapter 2 begins by offering a research-based analysis of the material science of wood and provides reasoning for choosing wood as a subject for investigation. This chapter also elaborates on the primary use of wood in today's construction industry. Chapter 3 contains a series of physical investigations conducted as part of the research into the properties of plywood. These findings are then implemented into small scale prototype models with the help of digital analytic and fabrication tools. Finally, Chapter 4 is devoted to proposing a full scale structural system which serves as a synthesis of the research, material analysis, digital fabrication and prototyping phases of the thesis.

The aim of the research is to reveal both the structural and architectural potential of plywood and to demonstrate some of the possibilities that can be achieved through an integrative design approach. The thesis presents an alternative design approach that seeks to understand wood's complex material makeup and behaviours in order to achieve novel ways of form-finding. In synthesizing these findings, the thesis aims to design a malleable, lightweight structural system.

In today's construction industry, plywood is considered a relatively mundane material, used primarily for sheathing purposes in roof, wall and floor assemblies. Unfortunately, the interesting bending and elastic properties of the material have not fully been explored regarding its potential for the architectural field. The research seeks to explore plywood's material properties in order to demonstrate new possible uses for the material in architectural design. The integrative design approach explored in the thesis can provide a renewed appreciation for plywood's amazing behavioural capabilities, allowing for new rich design opportunities.

1 Chapter: Theories on/of Materiality

Introduction: What is a Material?

In architecture, materials concern the applied use of a material or substance as a medium in a building or structure¹. This is an important and critical consideration, as materials can not only influence how a building is experienced or how a building is read in its context, but they can also have a remarkable impact on the performance of its architectural design. Furthermore, materials can play an important role in the act of *making* through their inherent properties such as elasticity, strength or stiffness. In this thesis, the word *material* refers to the materials employed while designing and their inherent properties and behaviours which can ultimately shape a design's development and performance.

1.1 Material and Form: A Separation in Architectural Practice

Throughout the history of western architecture, one can detect a growing division between form-making and its foundation in material conditions. In contrast, when considering traditional craftsmanship, it is evident that material and form are entwined in the process of making.² Material knowledge is essential for a craftsman to shape a material in order to yield maximum performance for a specific function. Modern design

¹ Penny Harvey and Conlin Casella Eleanor, *Objects and Materials A Routledge Companion* (Hoboken: Taylor and Francis, 2014), 81.

² Richard Sennett, *The Craftsman* (New Haven: Yale UP, 2008).

and modern means of production have evolved away from this integrated approach towards a process independent of its source in material knowledge. Rather, the modern approach lends itself towards the mass production, customization and compartmentalization of form making. That is, we select materials to suit a pre-determined form, rather than allowing the material to influence the form. As a result, materiality has become an agency secondary to form as technological advancements in construction and architecture continue to ensure that form is of unparalleled importance.

The cause of this shift can be associated to a number of factors such as the ever growing populace, or the need for mass housing, increased construction speeds and cost efficiency. In some cases, the building industry's modern approaches have proven to be beneficial, especially when faced with instances of emergency housing, accelerated projects or disaster relief. However, it is important to note that such ways of designing also contribute to negative implications including increased amounts of waste, non-sustainable practices and energy inefficiency.

One could even argue that form has become such an important part of the modern architectural design process that its precedence over material is now virtually intuitive. However, there exists certain exceptions in the work of influential educators and architects such as Josef Albers at the Bauhaus, Frank Lloyd Wright in the U.S.A, and later Frei Otto at the University of Stuttgart. The work of these three key figures serves as some of the earliest precedents in modern material exploration, physical computation and integrated design approach. Albers established a precedent surrounding material experimentation in which he identified material behavior itself as the creative domain for

developing new modes of construction and design.³ Frank Lloyd Wright introduced the concept of ‘organic architecture’ during the modernist era. This was an extension of the teachings of his mentor Louis Sullivan, who is considered by many as being the father of organic tradition in architecture. Wright’s core architectural philosophy surrounded the notion that “form and function are one,” and he used nature as the best example for this integration.⁴ For Wright, organic architecture did not entail a literal imitation of natural forms, but rather proposed that design should respect the properties of materials and foster harmonious relationships between form and function. Wright’s concept of organicism, like holism, attempts to integrate spaces into a coherent whole which combines context, space and structure in forming an "integrated" architecture. Frei Otto's extensive series of experiments at the University of Stuttgart, serve as amazing precedents of what is now referred to as material experimentation and physical computation. Otto investigated natural forms and a number of materials in order to apply the self-forming capacity and innate behaviours of various materials toward design. He sought to determine whether these investigations could be translated into structurally optimized systems. Otto's research is particularly impressive given that his findings were tested and translated into a variety of built projects such as the Multihalle in Mannheim which will be discussed in detail in Chapter 1.6.⁵

³ Saletnik, Jeffrey. “Josef Albers, Eva Hesse, and the Imperative of Teaching.” Tate’s Online Research Journal 7 (2007): 5-6. <http://www.tate.org.uk/download/file/fid/7298> (accessed July 20, 2014).

⁴ Kimberly Elman, "Frank Lloyd Wright and the Principles of Organic Architecture," <http://www.pbs.org/flw/legacy/essay1.html> (accessed July 20, 2014).

⁵ Frei Otto and Bodo Rasch, *Finding Form: Towards an Architecture of the Minimal* (Stuttgart: Axel Menges, 1992), 23-71.

1.2 Industrial Revolution (Material in the West)

"For the first time a machine processed energy, material and information. Man is involved neither as an energy source, nor as material or information processor, but initializes and controls the process. Man becomes the creator of the process while the machine is the creator of the products."

Christoph Schindler, 2007

The Industrial Revolution which took place between the late eighteenth to mid-nineteenth centuries resulted in machine-based manufacturing and mass production for Western civilization. As a result, the complexity once involved in the creation of form was replaced by the concept and practice of automation.⁶ Functionality became the leading standard, as form followed function and ornament, a concept of the prevalent craft culture, became a crime.⁷ The value of ancient craft and the integration of material and form regarding the construction industry were abandoned in favor of faster, easier, and cheaper building methodologies and manufacturing processes. Although this shift brought forth many advantages, one cannot ignore that with it came with significant losses. The close relationship between design and ancient craftsmanship, as well as the material and technical knowledge associated with such trades were beginning to be forgotten.

⁶ Charles Jencks, *The language of post-modern architecture* (New York: Rizzoli, 1984).

⁷ Kenneth Frampton and Futagawa Yukio, *Modern Architecture* (New York: Rizzoli, 1980).

1.3 Digital Revolution (Computer-Aided Design in the Digital Age)

One can speculate that the separation of materiality and form was divided even further by the introduction of computer-aided and computer-generated design via the Digital Revolution (or Digital Age). The Digital Revolution marked the transition from analog to digital technology, transforming the drafting board into the digital canvas.⁸ Many of these technological advancements opened up new possibilities for designers to explore formal expressions within the digital realm, with newfound ease. However, these advancements also contributed to the ever-growing divide found between form and material. Architects could now carry out designs while disconnected from the physical realm. They could work within digital constraints deprived of any material knowledge, characteristics, behaviours or physical limitations. In other words, form and materiality were becoming increasingly severed as form began to exist in the virtual, and materiality, selected from a menu, was merely designed to suit a form or was otherwise excluded from the process altogether. The act of conceiving a form was therefore left to digital tools while its physical manifestation only became a reality once constructed.

Since the early nineties, and since the growing popularity of digital design tools, one could argue that the use of these technological advancements in the practice of architecture contributed to the rise of the formalist movement.⁹ Complexity in formal and geometrical shapes has become the symbol of creativity within the digital design culture

⁸ Neri Oxman, "Material-based Design Computation." (PhD diss., Massachusetts Institute of Technology, 2010).

⁹ Oxman, "Material-based Design Computation."

which continues to prevail in the formalist work of many renowned architects such as Frank Gehry, Zaha Hadid, Rem Koolhaas and Daniel Libeskind.

Current developments in digital design tools including parametric software or Building Information Modeling (BIM) are gaining increasing popularity amongst the industry. Nevertheless, this new generation of digital tools still behaves similarly to previous software (eg: CAD) in that information is prescribed from geometry, and not vice versa. These technological developments still lack the fundamental link between form finding and materialization, as they do not consider physical laws, material constraints or structural behaviours. As Bruno Latour once pointed out,

"... four hundred years after the invention of perspective drawing, three hundred years after projective geometry, fifty years after the development of CAD computer programs, we are still utterly unable to draw together, to simulate, to materialize, to approximate, to fully model to scale, what a thing in all of its complexity is."¹⁰

Perhaps the only digital design development that has begun to address these issues is Design Computation. Design Computation concerns a novel area of design studies which deals with the development of new concepts and techniques in computing. The term 'computation', according to Achim Menges, refers to the processing of information. Menges defines Design Computation as "processes, in the form of algorithms or generative rules, from which a specific result is then brought about through the definition

¹⁰ Bruno Latour, *A Cautious Prometheus? A Few Steps Toward a Philosophy of Design* (Cornwall: Design History Society Falmouth, 2008)

and emphasis on influencing values and parameters."¹¹ Therefore, Design Computation can be understood as a digital design process that is procedure-based, is mathematically definable, and is based on quantities, rules and/or relationships. This process can generate forms or even particular designs based on algorithms that are governed by rules such as physical laws, environmental factors, material constraints and material properties.

The use of Design Computation has thus far been limited to the research-based fields of architecture, engineering and computer science. In other words, it is still in its developmental stages. In most cases, projects employing Design Computation consist of interdisciplinary research projects, involving architects, engineers, and computer science technicians. This is because Design Computation requires in-depth knowledge and understanding of coding and digital processes, which most architects lack. Even still, it is currently very difficult to attempt to model complex phenomena and behaviours using computation. For instance, one must first entirely digitize the complex anisotropic properties and bending behaviors of wood before attempting to generate forms that will mimic the response and behaviour of the specific physical material. Currently, it continues to be more feasible for an architect or designer to try to understand complex phenomena such as material properties through investigative acts of play and tactile exploration. When using this methodology, the designer can understand a material's constraints and capabilities before and while applying these findings to the design development process.

¹¹ Achim Menges, *"Form Generation and Materialization at the Transition from Computer-aided to Computational Design,"* Detail 04 (2010): 331.

1.4 Material Design

In more recent years, the architectural field has begun to see a renewed interest towards novel design approaches such as material-based design. One can see this in the sheer amount of research being conducted in graduate architectural programs around the world surrounding the themes of biomimicry, material research and morphogenetic design.¹² It is evident that the research and work of key figures like Achim Menges of the University of Stuttgart and MIT Professor Neri Oxman also continue to influence both students and professionals in this particular field of research.

Moreover, there is a growing interest in the potential of innovative material usage. Designers are beginning to turn towards material properties as a source of design inspiration. Examples of material classifications which continue to serve as design inspiration include biomaterials, responsive materials, as well as composite materials.¹³ The projects conducted at the University of Stuttgart and at Harvard University which are referenced above constitute precedents of work that have explored the design potentials of such methodologies.

In this thesis, material-based design is proposed as a strategy which can support the integration of form, material, and structure by incorporating physical form-finding strategies with digital analysis and fabrication. In this approach material precedes shape. That is to say, the design develops and emerges from material properties and its inherent

¹² (Hygroscope – Meteorosensitive Morphology research project by Achim Menges in collaboration with Steffen Reichert) or (Kerf-Based Complex Wood Systems a research project conducted at the Harvard University Graduate School of Design by Brad Crane, Andrew McGee, Marshall Prado, Yang Zhao).

¹³ Maltida McQuaid, *Extreme textiles: Designing for High Performance* (New York: Princeton Architectural Press, 2005).

behaviours. These material behaviours or constraints, such as strength, elasticity or breaking point, must first be understood through an investigative act of 'play' and tactile exploration. By conducting various physical investigations of the material, one can discover its potential as a building material. Once one understands what a material can do, one can start to incorporate this information into the design phase. Through this investigative knowledge of material properties, one can start to use digital design tools for analysis, development and precise documentation for fabrication.

The use of digital tools is essential in the thesis for precise form-generating procedures, which in turn paves the way for further physical analysis and development. Thus, the digital stages of the research are informed by the material properties and constraints obtained in the physical explorations, and yet facilitate the precise fabrication of prototype models for use in further experimentation. Here, one can see evidence of an integrative design approach, in which all phases continuously support one another. The digital tools employed during this research permitted for greater accuracy and increased efficiency in the overall design process.

This process thus involves a continuous feedback loop between material analysis, physical investigations, digital modeling, conceptualization and prototyping. The development of such integral design processes is advantageous as it incorporates material properties and strengths in approaching designs from an informed perspective.

Material research is becoming increasingly important in architectural practice due to several reasons. Such approaches build upon old design techniques and improves their implementation while also contributing to contemporary methodologies in architecture

such as morphogenetic design, design computation, biomimetic engineering and computer aided manufacturing. Material-based design also helps to address issues such as sustainability, cost efficiency, material performance, improved fabrication techniques and reduced waste.

It is becoming apparent that the modern design approaches which continue to be employed today have played a role in global environmental issues. For instance, the use of materials such as steel, aluminum or plastic which are widely used in today's building industries are non-renewable and contain high embodied energy.¹⁴ In a way, there appears to be a growing recognition of the inefficiency and waste resulting from such design approaches. That being said, the purpose of this comparison is not to state which approach is better than the other, but rather to understand the differences between integrated design approaches and modern design methodologies.

¹⁴ “Notes on Embodied Energy.” <http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=Notes>
“Embodied energy is defined as the energy used during the entire life cycle of a product including the energy used for manufacturing, transporting, and disposing of the product.” Last Modified 2014.

1.5 The Parts and the Whole (Mechanistic vs. Systemic)

"The great shock of the twentieth-century science has been that systems cannot be understood by analysis. The properties of the parts are not intrinsic properties but can be understood only within the context of the larger whole. Thus the relationships between the parts and the whole have been reversed. In systems approach the properties of the parts can only be understood only from the organization of the whole."

Fritjof Capra 1996

The debate between the philosophies of mechanism and holism has been a recurring theme.¹⁵ The two concepts relate to the relationship between the parts and the whole. The world view which accounts for an emphasis on the parts is coined "Mechanistic", while that which views the world as a whole is known as holistic or "Systemic" thinking.

Mechanistic thinking, otherwise known as *reductionism*, views the material universe, including all of its living organisms, like a machine composed of parts lacking any intrinsic relationship to one another. In principal, this machine could be understood entirely by the sum of its individual parts.¹⁶ In the mechanistic world view, complex systems are understood by subdividing or reducing the whole to its fundamental parts. For example, this can be seen in scientific research in which the processes of biology are reducible to chemistry and the laws of chemistry are subsequently explained by physics.¹⁷

The view of the world as a machine was pioneered by discoveries in physics, astronomy, and mathematics and eventually came to be known as the Scientific Revolution. It was

¹⁵ Fritjof Capra, *The Web of Life: A New Scientific Understanding of Living Systems* (New York: Anchor, 1996), 18.

¹⁶ Capra, *The Web of Life*, 20.

¹⁷ Capra, *The Web of Life*, 20.

associated with figures such as Galileo Galilei, Rene Descartes, Francis Bacon, and Isaac Newton, all of whom radically changed notions of the organic, living, and spiritual universe.¹⁸

On the other hand, the emergence of *systems thinking* came about as a response to the mechanistic shift (also known as the Cartesian-Newtonian paradigm). Systemic world view (or "systems thinking") is concerned with connectedness, relationships and context. It proposes the idea that natural systems and their properties should be viewed as an integrated whole, and not as a collection of parts. This view asserts that all things function as systems whose performance cannot be fully understood solely in terms of their component parts. Fritjof Capra, a scientist and writer who has engaged in systemic exploration in his research, expands on how systems thinking concentrates not on basic building blocks, but on basic principles of organization. He states that, "systems thinking is 'contextual' which is the opposite of analytic thinking. Analysis means taking something apart in order to understand it; systems thinking means putting it into the context of a larger whole."¹⁹

According to the systemic world view, "the essential properties of an organism, or living system, are properties of the whole, which none of the isolated parts contain. These overall properties are destroyed when the system is dissected, either physically or theoretically into isolated elements."²⁰ Thus, a system exists and functions as a whole through the mutual interaction of its parts. Although one can distinguish individual parts

¹⁸ Capra, *The Web of Life*, 23.

¹⁹ Capra, *The Web of Life*, 21.

within a system, these parts can never perform as part of the system in isolation. The nature of the whole is greater than the sum of its individual parts.²¹

One could very well argue that the mechanistic and systemic world views mirror the modernist design processes and the novel integrated approaches discussed earlier in the chapter, respectively. The mechanistic theory can be compared to today's conventional design approaches in many ways. Consider the common practices of linear work flows, in which all phases of a project follow one another in a linear, hierarchical and sequential manner. Each phase can only be conducted once the preceding phase has come to a close or has satisfied the necessary requirements. The issues which arise at various points as the project develops often require revisiting a previously completed phase in order to advance the project so that it may respond to newly identified requirements. This process adds iterative 'redesign' phases based on the feedback loop, and is contrary to the systems approach in which all phases are conducted simultaneously, consistently informing one another in a systemic manner. For instance, if a preliminary design is first conceived by an architect, and other project members then contribute their input based on specific areas of reparability -as in structural, mechanical and electrical engineers and/or building and fire code consultants- interiors are then “reworked” and laid out in order to operate consistently with the recommended structure and egress patterns. Only then can further design strategies, finishes and materials be decided upon and confirmed. Once the design phase is completed, the construction phase begins and such patterns are carried out once

²⁰ Capra, *The Web of Life*, 21.

²¹ Capra, *The Web of Life*, 29.

more in a similar fashion. All of these steps can be viewed much like the working parts of a machine devised for building design and construction.

In contrast, the research conducted in this thesis reflects the ideologies of the Systems world view. This is evident given the way that an integrative material-based design approach looks towards holistic methods of form finding. In these types of design approaches, form is not defined through a sequence of drawing or modeling procedures, but is rather informed and shaped by influences such as material properties, constraints, experimentation, and structural behaviours. These findings are obtained through a series of simultaneous explorations, prototyping and digital analyses which all serve to advance one another. As in the systemic world view, the synthesis of all these design processes is capable of producing results that are unexpected, and which would have been unattainable via any single isolated process.

1.6 How We Build: The Parts and the Whole - Precedent Case Studies

The two philosophies introduced above, mechanism and systems thinking, have influenced many aspects of our lives. One can arguably note their influences in our built environment, as can be seen in the variety of design methodologies present in architectural design.

Both academics and practitioners in the design field have often argued that the architectural practice can be classified as a holistic enterprise. This argument is founded on the fact that many players have a key role in the process of designing a building: the architect, the client, the consultants, the engineers, the planners, the builders and so on. In this context, holism does indeed propel an all-inclusive design process realized as a result of the many members collaborating on a given project. In fact, this trait is even said by many to be unique to architecture as a profession.

However, when analyzing the conventional design methodologies employed in architecture, one cannot ignore the hierarchical and sequential separation of design, detailing, documentation, modeling and fabrication. This type of hierarchical separation and compartmentalization of processes can be seen in many aspects of design, but more specifically between material, form and structure. In order to explain this phenomenon more clearly, two built architectural projects have been chosen for analysis based on these two ideologies in architecture. Analyzing the two built examples below may shed more light on the ways in which machine thinking and systems thinking have influenced architectural design philosophies and methodologies.

The first project can be considered the most contemporary technological application of timber construction. The second project was completed approximately three decades ago and continues to be an inspirational precedent regarding the use the inherent material properties of wood, specifically Tiber. Distinguishing between these two projects and their approaches is of great relevance to this research. The aim is not to assess the two projects with the intention of promoting one over the other, but rather to identify the contrasting design methodologies. For this comparison, the focus will lie namely on the design and realization of the roof structures.

Illustration 1 Centre Pompidou in Metz, 2010.

Illustration 2 The “Multihalle” Mannheim, 1975.

The inspiration for the roof of the Centre Pompidou in Metz, designed by Shigeru Ban, Jean de Gastines and Ove Arup & Partners, was a traditional Chinese straw hat (ill.3). The form that resulted from this inspiration was based on two components: a specified freeform surface with a hexagonal edge, and a flat, kagome lattice consisting of triangles and hexagons that is projected onto the free-form surface. The lattice structural grid was developed using digital processes such as CAD software (ill.4). The digital model created from this step was then developed into a highly complex geometric construction in which

every element of the structure was unique in its curvature and shape. The digital form-giving process was used only to establish the geometry of the roof structure. Following this design phase, engineers and consultants working in the realm of computer-based geometry optimized the design of the structure and rendered it buildable.

Illustration 3 Left: The Centre Pompidou's structural roof mesh. Right: The Chinese straw hat that inspired the roof structure.

Illustration 4 Top: A Kagome lattice pattern projected onto the free-form surface of the roof.
Bottom: The digital model of the roof structure for the Centre Pompidou.

The actual physical construction of this roof structure involved a series of glue-lam girders arranged in three layers (ill.5). Each of these girders is comprised of several segments, fastened to one another with steel brackets and dowels in order to achieve the "curved" appearance of the girders. In total, the entire roof assembly is made up of 1,790 segments, which were classified into three categories (straight, single curved, double curved) (ill.6). The 1,790 individual segments were fabricated by a computerized numerical control (CNC) joinery machine. In order to achieve the final form of the structure, it was necessary to mill away a substantial volume of material from each individual glue-lam beam to obtain the required building component geometry (ill.7). In the next phase of the project, the individual components making up the complex geometry of the roof were transported from the fabrication shop with trucks and were assembled incrementally using scaffolding and cranes to make up the final form of the structure (ill.8).

Illustration 5 The structural composition of the roof system, comprised of 3 double layer wood laths with rectangular cross sections.

Illustration 6 The various categories used in the fabrication of the roof segments.

Illustration 7 Left: The (CNC) machine milling off portions of timber canopy members
Right: Milled timber members.

Illustration 8 The construction of the roof assembly of the Centre Pompidou, Metz.

This project followed a relatively linear flow of data, beginning with the initial design inspiration, and working up towards a formal design, the development of a CAD model, the refinements and optimization achieved by engineers in rationalizing the process, and finally ending with the computer aided manufacturing of the highly specified components. A similarly linear approach then took place on site for the duration of the incremental assembly process. Overall, this design approach is a direct reflection of mechanistic ideologies.

Illustration 9 The “Multihalle” Mannheim, 1975 (Interior space).

The second project is the “Multihalle” located in Mannheim and designed by Frei Otto, Carlfried Mutschler, and Ove Arup and Partners (1975). Like the Centre Pompidou, this project consists of a double-curved lattice shell, but the design was not the result of a form-giving process (ie. one in which the form was pre-conceived by the designer and a

structural system was developed to actualize the form). Instead, this project consists of a more integrated form-finding process informed by material experimentation, material behaviours and constraints along with an extensive series of models and prototyping. It is important to note that the form-finding process for the Multihalle involved upside-down hanging chain models (ill.10). This was important because it allowed the architects to determine the three-dimensional geometry of a shell which they considered to be the optimal shape for the design. These models were especially effective in creating pure tension shapes due to gravity's pull on the chains. When an appropriate geometry was achieved, through varying parameters such as the length of the chains and the proximity of the hanging points (decided upon through the 'eye of the designer'), the model was then inverted to create a pure compression shell. This resulted in a geometry that was structurally stable, devoid of in-plane shear stresses in the lattice structure.

Illustration 10 The hanging chain model used in the design of the Multihalle.

In the development of this project, the lattice shell structure was based on two fundamental questions:

- 1) Could a shell structure be constructed with a tensile uniform mesh and be capable of supporting its own weight without buckling and causing no moment bending?
- 2) Could a shell structure be constructed using the natural bending properties of wood laths, which were initially assembled as a flat system?

The structure of Multihalle is called a *grid shell*. A grid shell is a "double curved surface formed from a lattice of timber laths bolted together at uniform spacing in two directions."²² There are two types of lattice shells systems: strained and unstrained. The difference between strained and unstrained shells is that the unstrained shells are made of pre-bent members. In the unstrained shell, curved members experience no strain during the erection process because they have been previously curved to the desired shape. This method was used for the Centre Pompidou in Metz. The Multihall shell structure however, consists of a strained lattice shell, comprised of a 2 double-layer wooden lath system, assembled flat in a square diagrid pattern (ill.11). The initially flat grid is held together by pinned joints (ill.12) that permit the laths to move parallel to one another (ill.13). This allows the grid one degree of movement when flat. However, once the structure is erected and the grid takes on the double-curved geometry of the shell, the forces will deform the square grids into parallelograms (ill.14). In this manner, the structural web can take on specific forms by changing key parameters in the assembly

²² Happold and Liddell, "Timber lattice roof for the Mannheim Budesgartenshau," *The Structural Engineer* 53 (1975): 99-135.

such as scissor-like deformation, adjustable pins, cambering and edge definition of the system. As a result of this double curved design, the members increase in strength and stiffness.²³

Illustration 11 The flat assembly of the lattice diagrid structure of the Multihalle.

Illustration 12 Multihalle's joint connection detail.

²³ Burkhardt Berthold and Frei Otto. *IL 13: Multihalle Mannheim* (Stuttgart: Freunde und Förderer der Leichtbauforschung, 1978).

Illustration 13 The lattice distortion of the Multihalle's diagrid structure.

Illustration 14 From flat to curved: The forces acting along the edges of the assembly cause the wooden laths to bend into a curved form.

Erecting the shell on site required that the entire flat system be lifted at a number of key points with the aid of cranes. Once the web was lifted at these points, the network of wood laths naturally took on the desired geometry due to the flexible bending behaviour of the continuous wood members and the deformation of the network (ill.14).

The system's joint connections were then tightened to obtain shear-resistant connections that would maintain the desired shape of the structure (ill.15). Next, steel cable ties were added to provide diagonal stiffness to the shell (ill.16). The grid shell was then fastened to the substructure at specified support points, thereby stabilizing the complex roof (ill.17).

Illustration 15 Workers tightening the system connections of the Multihalle.

Illustration 16 A diagram illustrating the Multihalle's system assembly via a steel cable brace.

Illustration 17 The Multihalle's substructure connection detail.

The critical difference between these two projects is that one was designed and geometrically defined by the designer and subsequently rationalized for construction, while the other was a result of an extensive form-finding process based on material behaviours, experimentation and structural behaviours. The Centre Pompidou is often referred to as a state-of-art, digitally designed wood construction project. It required six layers of glue-lam beams with cross section of 140 x 440 mm to achieve a 50m clear span. In addition, it was necessary that 50 percent of the glue-lam material be milled off during the CNC fabrication process in order to achieve the desired shape of each member. In contrast, the double layered grid of the Multihalle in Mannheim spans up to 60m and consists of members that only measure 50 x 50 mm in cross section. As a result, the “Multihalle” project emerged as a grid shell that was extremely cost-effective and

material efficient. It also proved much easier to construct than many of today's contemporary lattice structures like the Centre Pompidou in Metz.

The intention of this comparison is to demonstrate the differences which exist between these two design methodologies. One is the digital continuation of the long-standing hierarchical process in which form-giving takes precedence over rationalization. The other concerns a design process which undergoes constant transformations due to an integrated and informed approach that can anticipate the possibilities of materialization.

Frei Otto's work with lightweight structures as well as the design methodologies employed in his projects serve as exemplary precedents in demonstrating the theory and design methodologies adopted in this research. Similar to Frei Otto's approach, this research will propose a lightweight structural system that seeks to incorporate an integrative approach to form-finding using the material properties and behaviours of wood. In order to fully understand the capabilities of this material, the following chapter explores the material science and characteristics of wood.

2 Chapter: WOOD AS A MATERIAL

Illustration 18 Scanning electron micrograph of wood from a Siberian pine tree illustrating the internal biological tissue and structure of wood.

2.1 Why Wood?

"Timber is coming to the fore as a contemporary construction material. Not only sustainable, its suppleness, adaptability and strength make it highly attractive for experimental designers"

Markus Huder 2010

"Today we still do not have a material that rivals wood in its subtlety of structure and property"

Philip Ball 1997

Wood is quite unique when compared to most building materials used today given that its material makeup is a result of naturally grown biological tissue (ill.18). Thus, the material makeup and structure of wood is significantly different than that of most industrially produced, isotropic materials. Upon close examination, wood can be described as an anisotropic natural fiber composite. In contrast to *isotropy*, which constitutes identical properties in all directions of a material, *anisotropy* concerns the property of being directionally dependent. For instance, one can see this in the way that wood can bend easily in the *tangential* axis (ill.19) which is the direction perpendicular to its grain direction. When examining wood from any given angle, one can identify material characteristics and behaviours specific to that angle, relative to the material's main grain orientation. That is to say, should one examine the material properties of wood at an angle 45 degrees to the main grain orientation, one will discover properties extremely different than those obtained from an angle 90 degrees to the main grain orientation.

Illustration 19 The three principal axes of wood with respect to grain direction and growth rings.

The directionally dependent property of wood is a result of the horizontal or vertical orientation of the individual cells and the arrangements of growth layers in a tree.²⁴ This inherent heterogeneity of wood as well as its complex material characteristics have often been characterized as deficiencies by architects, engineers and members of the timber industry.²⁵ This can be traced to the fact that most designs and construction methodologies used today require the use of materials bearing minimal variations in their properties and behaviours in order to satisfy the need for isotropic structures.

In contrast, this thesis views wood's complex material makeup and its capacities as significant advantages rather than deficiencies. Furthermore, it aims to understand these interesting characteristics of wood and employ them through an informed design process.

In addition to these complex material properties, wood also presents many favorable characteristics including diversity, weight, strength, appearance, workability, cost and availability. Another factor that makes wood a very appealing material today concerns its

²⁴ J. M. Dinwoodie, *Timber: Its Nature and Behaviour* (London: E&FN Spon, 2000).

²⁵ T. Herzog, *Holzbau Atlas* (Basel: Birkhäuser, 2003).

overall ecological advantages. In light of the environmental challenges that the built environment is facing today, it is becoming increasingly recognized that very few building materials can rival wood's environmental benefits. Wood is a natural, renewable material that holds a very low level of embodied energy. It is known for its ability to reduce carbon dioxide emissions by storing CO₂ and also by substituting for materials with a high carbon content²⁶. In this manner, the use of wood actually produces a positive carbon footprint.²⁷ Wood is also an extremely energy efficient building material in its production. For example, wood requires 50 times less energy in its manufacturing than steel to ensure a given structural stiffness as a whole.²⁸

Unlike many natural resources, forests consist of a renewable resource. With careful forest management, one can ensure that forests thrive and continue to provide the many benefits to which we have become accustomed. Foresters can calculate an 'allowable cut' of trees per year for any given forest area that will secure a stable harvest. Tree farming is yet another way of sustainably satisfying today's demand for wood. Programs at Oak Ridge National Laboratory have engineered a breed of super trees that can grow at rapid speeds in order to create a substantial amount of bio mass in a single given acre. These engineered trees are being farmed at tree farms such as the Boardman Tree Farm LLC, and are redefining modern forestry (ill.20). The Boardman Tree Farm plantations are located in eastern Oregon, United States, where dry desert land has been transformed into a thirty thousand acre farm. This plantation currently has seventy million trees and is

²⁶ A. Alcorn, *Embodied Energy Coefficients of Building Materials* (Wellington: Centre for Building Performance Research, 1996), 92.

²⁷ Joseph Kolb, *Systems in Timber Engineering: Loadbearing Structures and Component Layers* (Basel: Birkhäuser, 2008), 19.

²⁸ J.E Gordon, *Structure* (Cambridge: Da Capo Press, 2003).

capable of producing half a million trees every year to satisfy demands. The plantation harvests five acres of trees every day in order to maintain this continuous cycle.²⁹

Illustration 20 The Boardman Tree Farm plantations. Top: Satellite view of the plantations. Bottom: Aerial views of the plantations.

²⁹ "A Resource That Lasts Forever," last modified July 23, 2014, <http://www.greenwoodresources.com/>

2.2 The Complex Material Behaviours and Characteristics of Wood

As a result of wood's naturally-grown origin, its unique material composition accounts for most of its properties and characteristics.³⁰ This thesis aims to explore possible ways of utilizing the material properties of wood in design. In order to do so, the heterogeneous structure of wood must first be understood in greater detail.

Wood can be defined as a low-density, cellular, composite material and as such, does not readily fall into a single class of material, but rather overlaps a number of classes. In terms of its high strength performance and affordability, timber remains the world's most successful fiber composite. On the microscopic scale, one can describe wood as a natural fiber composite.³¹ (Ill.21)

Illustration 21 Layered cell wall structure of wood, illustrating the orientation of the Micro-fibrils contained within each layer.

³⁰ Barnett and Jeronimidis, *Wood Quality and its Biological Basis* (Oxford: Blackwell CRC Press, 2003).

³¹ "Composite Materials - Natural Woods." Last modified July 23, 2014, <http://www.technologystudent.com/joints/composit1.html>.

"Composite materials, sometimes referred to as composites, are materials composed of two or more component parts. These component parts may have different physical or chemical properties and when carefully inspected, they appear as separate parts, bonded together, forming a composite material.

Wood cells are comprised of layers, upon which cellulose microfibrils function like fibers embedded in a matrix of lignin and hemicelluloses, reinforcing the assembly as a whole. Due to this makeup at the microscopic level, wood shares a number of properties with materials like: synthetic composites, reinforced plastics, fiberglass, and carbon fiber. Similar to wood, these materials are characterized with relatively low stiffness in combination with relatively high structural capacity. In other words, wood contains innate elastic properties especially well-suited for construction methods that seek to employ elasticity in achieving complex lightweight structures from initially planar elements.

What follows is intended as a brief overview of the material composition of wood. Understanding the properties of wood is critical to the exploratory research that has been conducted.

In contrast to building materials that are specifically designed and manufactured to suit the needs of an architect or an engineer, wood is a result of the biological tissue functions that take place in a tree. Although there exists a wide variety of species of trees in the world, all trees, despite their diversity, share certain characteristics. Trees are all vascular and perennial which means they are capable of adding yearly growth to previously grown wood. The growth process of a tree occurs in the *cambium*, a thin layer of living cells between the bark of the tree and the inner stem structure. (Ill.22) Cambial cells have thin walls and divide themselves lengthwise to grow into two new cells. Following the cell division, one of the two cells enlarges to become another cambial mother cell while the other either matures into a bark cell or forms towards the inside of the cambium to become a new wood cell.

Illustration 22 Illustration showing the cambium layer of wood.

When the primary wood cells reach maturity and develop into their full size, a secondary wall is constructed from long chain hemicellulose and cellulose molecules. The long chains of cellulose molecules are oriented in a direction parallel to the long axis of the cells and reinforced by lignin (ill.23). Lignin is an integral part of the wood's cellulos structure because it provides support for the cells. It is also the material that gives rigidity to plants.³² The distribution and orientation of the cells along with the material structure of the cell walls determine most of the resulting characteristics and properties of wood.³³

³² R. Bruce Hoadley, *Understanding Wood: A Craftsman's Guide to Wood Technology* (Newtown, Conn.: Taunton Press, 2000).

³³ R. Wagenführ, *Anatomie des Holzes : Strukturanalytik, Identifizierung, Nomenklatur, Mikrotechnologie* (Leinfelden-Echterdingen: DRW-Verlag, 1999).

Illustration 23 The composition of wood, comprised of three main substances: Hemicellulose, Cellulose and Lignin.

Illustration 24 Left: The cell structure of softwood. Right: The cell structure of hardwood.

Trees are characterized into two types: softwoods and hardwoods (ill.24). The terms ‘softwood’ and ‘hardwood’ do not signify softness or hardness of wood. The two terminologies are related to the botany of the species and to the way in which a tree grows. The differences between the two types of wood can be seen in the cellular structure of the materials.³⁴ In the relatively simple cellular structure of softwood, nine tenths of the wood volume consists of one cell type called "tracheid", while the remainder consist of ray tissues. Tracheids are fiber-like cells and have a length-to-width ratio of 100:1, meaning that they are approximately one hundred times longer than they are wide. The tracheid cells are arranged parallel to the stem axis located in the radial layers of the tree and are responsible for the transport of water and minerals throughout the tree.

Illustration 25 Diagram illustrating the cell structure of vessel elements and tracheids.

³⁴ "Hardwoods & Softwoods," Last modified July 29 2014, <<https://www.canadianwoodworking.com/get-more/hardwoods-softwoods>>.

In contrast, a much greater variety of cell types and arrangement configurations are present in hardwoods. In addition to tracheids, hardwoods also contain vessels, rays and fiber cells. Vessel elements in hardwood have a large diameter and thin walls, containing no end-to-end walls. As a result, they are arranged in an end-to-end formation that is parallel to the stem axis of the tree, forming continuous channels that carry sap through the tree. Unlike vessels, fiber cells are much smaller in diameter and have thicker cell walls and possess closed tapered ends (ill.25). In both softwood and hardwood, the structure, distribution and orientation of cells are the determining factors of the anisotropic, structural, and hygroscopic characteristics of wood.³⁵

The anisotropic and hygroscopic characteristics of wood resulting from its internal cellular structure have traditionally been regarded as problematic in the practices of architecture and structural engineering, especially when compared to more homogeneous, stable, industrially produced isotropic materials like steel, plastic or glass. In design approaches within architecture, engineering and timber industries, knowledge of wood's material composition and characteristics has mostly been employed to counterbalance its complex material behaviours.³⁶ For instance, the development of engineered industrial wood products (ex: MDF, or cross-laminated-timber) came as a response to the heterogeneous composition of wood. These wood products are capable of producing a material that is much more homogenous and which provides isotropic material characteristics.

³⁵ R. Wagenführ, *Anatomie des Holzes : Strukturanalytik, Identifizierung, Nomenklatur, Mikrotechnologie* (Leinfelden-Echterdingen: DRW-Verlag, 1999).

³⁶ T. Herzog, *Holzbau Atlas*. (Basel: Birkhäuser, 2003).

Unfortunately, the design opportunities that could be made possible using the innate heterogeneous characteristics of wood are too often overlooked in today's construction projects. In fact, particularly in North America, the construction material of wood is often no longer referred to as such. Instead, wood is referred to as a dimensional building element, such as a '2x4'. The aim of this research is to propose an alternative approach to design which views wood's complex material composition and related behaviours as advantageous rather than problematic. Such an integrated design approach can perhaps contribute towards a renewed appreciation for the behavioral capacities of wood and the rich design opportunities that can be realized thanks to the natural anatomy of this material.

2.3 Plywood and Veneer

Three-ply plywood and veneer are unmistakably industrially-produced materials. However, unlike other industrially-produced materials such as steel, glass, plastic, MDF or particle board, three-ply plywood and veneer are anisotropic materials. This signifies that the properties and behaviours of these materials vary significantly in relation to the fiber direction. For example, veneer and plywood encounter considerable differences in stiffness depending on the grain direction. The compressive strength of wood differs significantly depending on grain direction, as do most of its other mechanical and material properties. The following section details the manufacturing process of veneer and plywood in order to better understand the material exploration that will be presented in Chapter 3.

2.3.1 Production of Plywood

Plywood may appear to be a relatively new industrially-produced wood product, however its concept is in fact very old and can be traced back to more than 5,000 years. Before the word “plywood” was invented in the 1920s, the process was referred to as *veneering*. One of the earliest traces of plywood was found in the tomb of King Tutankhamun, an Egyptian Pharaoh who ruled around the year 1334 BC. The discovered pieces of plywood were remains of coffins made of six layers of wood, each 4mm thick and held together by glue and wooden pegs.³⁷ The plywood remains were fabricated using the same fundamental techniques as today. Like modern plywood, the grains of the layers were arranged perpendicularly with each layer for strength (ill.26).³⁸ From this period onwards, veneering techniques became increasingly widespread throughout the world. Thanks to the development of tools and technology over the years, veneer thicknesses were reduced and new adhesives (ex: glue made from bone, sinew and cartilage) were used to bond the layers together with heat.³⁹

Illustration 26 Plywood’s cross laminated construction assembly. The arrows indicate the grain direction of the veneer sheets.

³⁷ Lucas A. and Harris, *Ancient Egyptian Materials and Industries* (Dover Publications; 4th edition, 2011), 451.

³⁸ H. Taylor John, *Death and the Afterlife in Ancient Egypt* (Chicago: U of Chicago, 2001), 218.

³⁹ L. Patrick Robert and Minford J. Dean, *Treatise on Adhesion and Adhesives* (CRC Press, 1991), 3.

Although plywood is made much in the same way today, modernized adhesion techniques and tools used in its production have improved significantly, making it one of the most affordable and easily-produced building materials. Both hardwoods and softwoods are used in the production of plywood. The typical sequence of operation involved in the production of veneer to be used in the manufacturing of plywood is as follows:

Illustration 27 The production process of veneer sheets.

Log Processing

The selected trees are cut down and trimmed into logs. The logs are then processed through a debarking machine (ill.28) and then cut into sections measuring typically between 8' 4" (2.5 m) to 8' 6" (2.6 m) with the use of circular saws. These sectioned logs are usually referred to as "peeler blocks".

Illustration 28
A debarking machine.

Log Conditioning

In this step, the peeler blocks are conditioned via steaming or soaking in hot water in order to soften the wood tissues for the next step. Typically, this process takes 12-40 hours depending on the wood type and diameter of the log.

Lathing

The conditioned blocks are then transported to the rotary lathe (ill.29), where they are aligned horizontally and fed into the lathe one at a time. Here the blocks are rotated along their long axis while a long sharp blade is pressed against the block causing a thin layer of wood to peel off in a continuous sheet of veneer.

Illustration 29 A rotary lathe, used in the manufacturing of veneer sheets.

Drying

The sheets of veneer are then stacked and placed into a steam or gas heated dryer to reduce their moisture content, allowing them to shrink. After the sheets have dried, they are then sorted and cut to appropriate widths: usually 4' 6" (1.4m) if manufacturing the standard 4' (1.2m) wide plywood sheets.

Veneer Bonding

The production of plywood begins with the process of laying up and gluing the veneer sheets together. In a three-ply plywood sheet, the first base veneer sheet is laid flat and is run through a glue spreader, which applies an even layer of adhesive to the top surface of the sheet. The next core veneer sheet is then placed on top, perpendicular to the grain direction of the first sheet. The two stacked sheets are then run through the glue spreader

one more time. Finally, the third and final face veneer sheet is laid on top of the glued core, in the same direction as the base sheet. The cross-lamination provides superior dimensional stability and resistance to warping or buckling when exposed to moisture. The completed three-ply sheet is then stacked with other completed sheets before undergoing the *pressing* step.

Pressing

The glued plywood sheets are loaded into a hot press (ill.30). The pressing machine can press twenty to forty sheets at a time, with each sheet loaded into a separate slot. When all the sheets have been loaded, the press squeezes them together under high pressure while at the same time heating the sheets. This ensures good, uniform contact between the layers of veneer, while the heat also allows the glue to cure properly for maximum strength. After the plywood sheets are cured, they are then trimmed to their final dimensions (typically 4' by 8') and sanded with belt sanders, which sand both faces in order to give them a final finish.

Illustration 30
A hot press machine, used in the lamination process of plywood.

There exists a long standing discourse on the subject of sheet materials in architecture, in part because these are so ubiquitous in conventional construction. Expanding the understanding of these materials is valuable to the architectural profession, as it allows one to discover new potentials concerning materials which are already familiar. Being a sheet material, plywood thus offers many advantages as a subject of research and experimentation. Like other sheet materials, it can facilitate the creation of complex geometry using initially planar elements. Three-ply plywood is the material of choice for this thesis due to its ability to offer high amounts of flexibility in one direction, without compromising its strength. Three-ply plywood, as previously described, is made up of odd layers, two of which are oriented in one direction, while the center layer lies perpendicularly to the outer layers. Thus, due to the predominant fiber direction present in the two outer layers, three-ply plywood possesses a natural tendency to bend perpendicularly to this grain direction. The core of the assembly, otherwise known as the center layer, provides strength to the assembly by offering resistance to the predominant fiber direction. As a result, the plywood assembly is less likely to break or snap when being bent because it is reinforced by one interior sheet containing fibers running perpendicular to the outer layers.

Knowledge of the manufacturing process for plywood is important for this research because it provides an introduction to lamination techniques that can be further utilized in the material investigations and implementations that will follow. The process described above elaborates on the procedures involved in the mass-produced manufacturing of flat plywood sheets used in the building industry. However, the process of lamination need

not strictly apply to planar surfaces, but also to the development of three-dimensional forms.

2.3.2 Plywood Precedents

In the past, similar lamination techniques have been used by craftsmen, designers, and architects in the creation of complex forms. Some of the earliest examples involving the application of lamination processes towards the creation of three-dimensional forms are a series of designs completed by Alvar Aalto. Aalto experimented with a variety of different construction materials including steel. His most famous explorations are with laminated materials such as birch and plywood. Aalto designed a series of plywood chairs made from laminated and solid birch frames. He utilized the flexible material characteristics of wood in order to create the complex forms of his furniture. He designed the undulating seat that conforms to the human body using bent plywood which had been created through a lamination process that made possible its complex shape (ill.31). He also used the flexible and “spring-like” behaviours of the wood to allow his chairs to bend or flex in relation to the weight of the person sitting on them. Aalto’s design methodology was very different from the modern movement at the time; He believed that design should be both natural and organic and must be advanced via holistic approaches. He rejected the use of mass production and man-made materials such as steel in his

designs⁴⁰. This can easily be seen in the organic and distinctive appearance of his furniture designs.

The works of Charles Eames and Ray Kaiser Eames is another great early precedent surrounding plywood and lamination techniques. Charles Eames and Ray Kaiser Eames were architects and designers who pioneered the use of new materials and related techniques. During the 1940s, they were exploring wood-molding techniques that eventually lead to the development of plywood splints, stretchers and glider shells for the US Navy (ill.32).⁴¹ After this involvement, they applied the developed technical processes of plywood molding towards the design of furniture. Over the course of their careers, they designed a number of chairs which were created using the concept of plywood lamination. As a result, they were successful in achieving three dimensional forms that could comfortably accommodate the human body (ill.32).⁴² The Eames design methodology stemmed from numerous prototypes and rigorous explorations. Their approach consisted of tactile iterative processes reminiscent of traditional craft culture. They thus followed a methodology in which the design was in a constant state of transformation as it develops.

⁴⁰ "Alvar Aalto and his laminated wood and plywood furniture," last modified August 1, 2014 <http://www.design-technology.org/alvar1.htm>.

⁴¹ "Charles + Ray Eames," last modified July 30, 2014, <http://designmuseum.org/design/charles-ray-eames>

⁴² "Heilbrunn Timeline of Art History" last modified July 30, 2014, http://www.metmuseum.org/toah/hd/eame/hd_eame.htm.

Illustration 31 The images above depict the Model No. 41 lounge chair and the Model No.31 cantilever laminated wood chair, designed by Alvar Aalto.

Illustration 32 Left: Eames Splint for the U.S. Navy, 1942. Right: Eames DCW side chair, 1946.

More recent uses of plywood and lamination techniques in the architectural field can be seen amongst research projects such as the “Aggregated Lamination” or “ICD/ITKE Research Pavilion 2010”, both conducted and led by Achim Menges at the Institute for Computational Design of the University of Stuttgart as well as the Radical Wood Pavilion by Dr. Jarkko Niiranen completed at Aalto University, in Helsinki.

The Aggregated Lamination project explores some of the material properties of wood veneer and makes use of digital fabrication tools and lamination techniques in order to create an isotropic shell structure. The research component which employed digital fabrication methodologies was critical to creating complex molds that would guide the lamination processes of the structure’s complex forms (ill.33).⁴³ The main objective of this research was to investigate the anisotropic properties of wood veneer and to employ isotropic lamination techniques in a design project.

The ICD/ITKE Research Pavilion project consisted of a temporary pavilion constructed by an interdisciplinary team of architects, engineers, software developers and programmers in order to showcase some of the latest developments in material-oriented computational design, simulation, and production processes pertaining to architecture.⁴⁴ Once again, this project focused on the material properties and physical explorations of plywood with the aim of creating a lightweight structure made entirely of very thin, elastically-bent plywood strips. The pavilion is constructed of initially planar birch plywood elements which were bent in such a way as to achieve the final, structurally

⁴³ "Aggregated Lamination," last modified August 1, 2014, <http://www.achimmenges.net/?p=5011> (accessed August 1, 2014).

⁴⁴ "ICD/ITKE Research Pavilion 2010," last modified August 1, 2014, <http://www.achimmenges.net/?p=4443>.

sound geometrical composition of the pavilion (ill.33). One of the most noteworthy aspects of this project concerned the fact that the final form of the pavilion was conceived using a developed parametric design software which incorporated the material properties and constraints of plywood into a digital model. In this way, this project proposed a novel approach to computational design which allowed for architectural form-making driven and informed by physical behavior and material characteristics. These material-informed “driving agents” of design were made possible through the extensive series of physical experiments conducted by the team in Stuttgart⁴⁵.

The Radical Wood Pavilion project is another example which adopts novel uses of plywood and incorporates an integrated design approach. Like the ICD/ITKE Research Pavilion, this project also involved a multi-disciplinary team. The goals of this project were to utilize digital design and analyzing methods while exploring digital manufacturing processes, the aim was to advance the collaboration between architecture, design and structural engineering via new, holistic working methods. As a result, this project investigated, studied and tested the bending and structural properties of birch plywood in order to create the final structural composition of the pavilion (ill.34).⁴⁶ These three research projects thus serve as some of the most recent and significant developments surrounding material-informed, innovative uses of plywood in an architectural setting.

⁴⁵ "ICD/ITKE Research Pavilion 2010"

⁴⁶ "RADICAL WOOD PAVILION," last modified August 1, 2014, <http://eerolunden.com/2012/12/18/radical-wood-pavilion/>.

Similarly to the processes and methodologies used in the fabrication and design of furniture by the Eames and in the research projects conducted by Achim Menges and Dr. Jarkko Niiranen, this research adopts lamination techniques and tactile exploratory processes towards discovering novel integrated design approaches. The following chapter presents further evidence of the material behaviours and characteristics of plywood, obtained through such explorations. Through a series of investigations and prototypes fabricated with the aid of digital tools, the malleable properties of plywood are further explored. The purpose here is to develop an increased understanding of plywood as a material in order to apply its unique behaviours and characteristics towards the process of designing a lightweight structure. This dynamic, lightweight multi-layered structural system will be developed and assembled using both the techniques and material findings obtained from the research and investigations. The proposal, presented in the subsequent chapters of this paper, will aim to satisfy structural and architectural demands achievable through the anisotropic properties of wood.

Illustration 33 Top: Aggregated Lamination process used during the construction of the ICD/ITKE Research Pavilion in Stuttgart. Bottom: Images of the overall ICD/ITKE Research Pavilion 2010.

Illustration 34 Radical Wood Pavilion.

3 Chapter: Material Experimentation and Implementation

3.1 Background Research (Hub Ottawa – Resonant Project)

The research began in the summer of 2013 with an academic workshop titled “Structural Morphology” conducted by professor Manual Baez at the *Azrieli School of Architecture and Urbanism* of Carleton University. For this workshop, Professor Baez and the participating students were given an opportunity to design and install a ceiling installation that would be permanently displayed in the community space of Hub Ottawa. Hub Ottawa is an organization that seeks to provide a platform for collaboration to its members comprised of innovators, designers, entrepreneurs and artists in order to collectively create a positive impact for the community.⁴⁷

The installation that came to be realized through the Structural Morphology Workshop was titled “Resonant Currents”. The aim of this project was to design an art installation that reflected the collaborative values of the Hub Ottawa organization, as well as the interconnectedness between cultures within Canada and throughout the world.

In the creation of this installation, the project was based on two fundamental investigations:

1) Pattern Inspiration

The workshop began with discussions surrounding the organic nature of patterns, and their origins in nature, man-made objects and science. The investigation of various natural and man-made patterns found throughout the world was conducted as a means of

⁴⁷ “HUB Ottawa,” Last Modified July 23, 2014, <http://ottawa.the-hub.net/>.

raising awareness about these patterns, and as a source of design inspiration. During this phase, the workshop participants studied patterns from nature, science, ancient scripts, weaving techniques, neural mapping images, calligraphy and aboriginal art.

2) Form Finding (Material Design Explorations)

The second part of the investigation involved novel ways of investigating plywood and its properties as a construction material for the installation. Russian birch plywood was chosen as the material employed in the fabrication of the project primarily due to its innate bending material characteristics and cost efficiency. However, an alternative perspective towards this seemingly common material had to be adopted in order to fully understand the potential of the material and its capacities. For most of the students involved in the project, the idea of utilizing the bending behaviours of plywood was rather unfamiliar. This is because plywood is mostly perceived as a mundane construction material used only for sheathing, membranes or roofing, all of which consist of planar assemblies. Thus, the final form of the installation was a result of numerous tactile material explorations and form-finding exercises.

The Development of the Installation:

Illustration 35 Resonant Currents project: A preliminary installation located at Carleton University.

The installation is comprised of 4" wide plywood strips that were cut from a square plywood sheet measuring 5' by 5'. These strips were cut perpendicularly to the predominant grain direction of the sheet, allowing the strips to bend lengthwise (ill.36). The bending characteristics of the 3-ply plywood strips were analyzed via a series of form-finding exercises which eventually led to the intricate forms and soft curves of the installation. These form-finding exercises resulted in the development of a double strip unit. These units are composed of two 4" wide by 5' long plywood strips that are entwined together and which serve as the basis for the entire network of the installation (ill.37). Through the act of mirroring the assembly of these individual units, the creation of two identical yet mirrored units could be achieved for use in the design. Thus, the only difference between these two double strip units is the direction in which the strips are

twisted together. The two strips that make up each of these units are fastened together at both ends using four bolts. This design permitted the units to be fastened together, end to end, in a continuous fashion (ill.38). Furthermore, the joints also allowed for the strips to meet and become fastened at various angles when weaved together (ill.39). The development of this overall system allowed for complex patterns and geometries to be created from only these two basic primary units.

Illustration 36 Double strip unit used in the design and fabrication of the Resonant Currents project. Illustration depicts the sequence of assembly.

Illustration 37 A single double strip unit.

Illustration 38 A multiple unit assembly.

Illustration 39 Connection detail used to fasten units to one another.

Illustration 40 The developed and finalized formation of the installation.

Once the units were fastened together and began to take the form of long chains, the assembly started to behave in a peculiar manner due to the fiber direction of the plywood strips. The resulting network assembly was designed and constructed based on the innate behaviours of the double strip units. In this manner, the design reflected the ways in which the units naturally sought to bend and twist, rendering their self-organizing properties. In other words, the units were able to generate forms and patterns within the given constraints of the assembly process. Together, the components of the assembly and their combined behaviours allowed for the formation of the installation's pattern. Therefore, it is through this integrated design approach that the behaviours of individual components and their interactions as a whole resulted in the interesting form of the final design (ill.40).

Once the final iteration of the installation was achieved, and all issues had been resolved, the assembly was dismantled into its components in order to be transported from Carleton University to Hub Ottawa, where it was reassembled and installed as per the final design (ill.41). Given that all units were identical, the transportation and re-assembly of the installation could be undertaken with more ease than if each component had been customized in its fabrication. The final installation was completed in September 2013 and was showcased to the public and the Hub Ottawa community on September 20, 2013.

The Resonant Currents project was a critical departure point for the research because it served as an introduction to the material plywood and the concept of material-based design. The project established notions and methodologies that serve as a foundation for the research herein. After the completion of the Resonant Currents project, the research led to a continued investigation of plywood through further in-depth material

explorations and prototyping. The criteria of this investigation was to determine the potential of plywood as a building material so that it may go beyond art, and be used in the creation of an active lightweight structural system.

Illustration 41 The Hub Ottawa space showcasing the finished installation from the Resonant Currents project.

3.2 Material Investigation

3.2.1 Structural Experiments

The first test conducted in this phase of the research aimed to understand plywood's bending capacities by demonstrating how wood generates different shapes when it is subjected to external forces. This was conducted by subjecting a strip of 3-ply plywood to forces being applied from both sides (ill.42):

Illustration 42 A simple physical test in which two forces act on a single (3-Ply) plywood strip.

This exploration illustrates the deformation characteristics of plywood that are triggered when subjecting the material to external forces. By sliding the tabs of the frame upon which a strip of plywood is placed, the plywood strip arranges itself into a variety of angles and forms in response to the stresses being applied. As shown in illustration 43, one can clearly see the range of motion that the plywood strip is able to adopt due to the parameters subjected by the frame. This test also demonstrates the notable strength with which the material is capable of bending. The plywood strip was bent at remarkable angles without breaking or splitting thanks to its cross-laminated material composition described in Chapter 2. Although such a test may appear basic, properly understanding the bending behaviours of plywood when subjected to external forces is essential to the

development of a structural system which aims to use plywood's unique properties towards achieving unprecedented results.

Illustration 43 The self-organizing formations of plywood when responding to applied forces.

Structural Prototype #1

In this series of explorations, the following explorations sought to determine whether the bending behaviours of multiple strips of plywood could work in unison as a system towards reshaping the overall form of the assembly. In order to put this phenomenon to the test, a model was fabricated using three 2" by 5' strips. The assembly contained a 'core' (web) strip and two 'cap' (chord) strips. When flat, the assembly resembled a Warren steel truss, the bottom and top 'cap' strips acting like chords, while the 'core' strip behaved much like a web (ill.44).

Plywood Truss Assembly

Illustration 44 Structural prototype #1: active plywood truss component.

The chords are pierced with 2" slots located at 12" intervals while the web is drilled with 1/4" holes located at 6" intervals. The core strip is fastened to the top and bottom strips via the slotted grooves, giving the resulting truss a sine-cosine web pattern. The assembly thereby deforms itself into an active bending truss system that can be manipulated by adjusting key parameters of the system. The slots in the bottom and top strips allow the nodes to slide back and forth in a direction parallel to the laths. Like the tabs used in the first material explorations, this ability for the nodes to shift applies varying amounts of force to the web strip, thus resulting in the deformation of the system assembly. As seen in illustration 45, the assembly is capable of experiencing a high range of movement due to the permitted oscillation of the nodes and the bending behaviours of the material. The system is also capable of withstanding enormous amounts of bending without compromising strength due to its truss-like design. However, these tests were also critical in discovering the system's maximum bending threshold. Illustration 46 depicts the breaking point of the model used in the experiment. The information obtained in this series of tests was recorded and analyzed for future implementation in prototypes and explorations dealing specifically with the breaking point of plywood strips and the range of bending which this material can withstand under varying parameters.

Illustration 45 The bending behaviours of an active plywood truss component.

Illustration 46 Illustration of the breaking point of the system web (establishing the system's maximum bending strength).

3.2.2 Skin Explorations

“Structure and skin is the determinant system by which buildings are designed and built and yet is only the skin we see. Flat, rectilinear panel grid themselves across the built environment hiding the truth of the structure that suspends them”

John Hillyard 2013

This next part of the investigation deals with the application of plywood as a ‘skin’. The tests undertaken during this phase aimed to determine whether a skin system that could react and deform to a changing substructure could be developed using plywood. Most building skin systems in architecture are designed as static components that cover a building’s structure and protect it from the elements. This was indeed the case with the “Multihalle” project in Mannheim. Although the structure of the Multihalle was malleable, the skin which covered it did not reflect the properties of this substructure. In fact, the skin system of the Multihalle was made up of individual square PVC coated sheets that were applied to the exterior of the shell structure after it was erected (ill.47) This process is yet another example of a separate construction procedure that was devised in isolation from the rest of the design (i.e.: isolated sequential design development).

Illustration 47 Workers applying the skin of the Multihalle.

In contrast to this, one of the criteria for the proposal designed as part of this research required that the self-supporting system be covered by a skin that was capable of reacting to the substructure. In other words, unlike the Multihalle project, the skin and structure would work together, achieving a unified design capable of serving as structure and envelope simultaneously. In order to undertake this challenge, an investigation was conducted surrounding biological systems to discover how nature opts to manage these situations, herself. There exists many examples of integrated relationships between skin and structure in the natural world. For instance, these can be perceived in the anatomical scales that cover the bodies of various species around the world such as fish, reptiles, mammals and plants (ill.48).

Illustration 48 Scale anatomy as found in biological examples: (Left) fish & shark (Middle) reptiles (Top Right) Plants & trees (Right Middle) mammals (Right Bottom) Insects: butterfly.

The scales of these species were studied and examined in close detail specifically those of fish and sharks, in order to incorporate properties of these biological examples into a series of design explorations. These explorations and tests aimed to determine whether a “scaling” strategy could be employed in the design of an active skin for the final proposal.

Skin Prototype #1

This investigation explored the shape, pattern, composition, and bending behaviour of shark scales as a source of inspiration for the design of a “scaled” skin prototype. Wood veneer was chosen as the material to create these scales because of its directional fiber-orientation and elastic bending properties. However, before utilizing the material in a form-finding design, a better understanding of its capacities and constraints needed to be obtained through tactile investigations. Through this understanding of the properties of the veneer, it was then possible to design a “scale” which took into consideration the material’s physical capabilities. Thus, the form of a single ‘scale’ adopted the stylized appearance of a shark scale, and was developed using digital modeling software which was informed by the material properties of the wood veneer. Similar to shark scales, the form of the scale adopted a sine wave profile, as well as a tapered geometry that would allow for the overlapping of multiple scales (ill.49).

Illustration 49 The development of a single stylized scale prototype, inspired by shark scales.

In order to construct a physical prototype of the scale, a mold was first required. This mold was conceived of using the same digital modeling file that was used in developing the scale (ill.50). The mold was fabricated from a 1' x 1' x 6" MDF block which was milled using a computer numerical control (CNC) router (ill.51).

Illustration 50 The digital model of the mold used in the lamination process of the scale prototype.

Illustration 51 The (CNC) machine milling off portions of the mold (3/4 Stacked MDF, Hights 3").

Next, in order to fabricate a single scale, laser cutting was used to cut out two rectangular pieces (8" by 4") of 1mm birch veneer (ill.52). It is important to note that the veneer cutouts were cut perpendicularly to the grain direction of the veneer sheet in order to allow the veneer pieces to drape against the mold (ill.53). The two resulting veneer pieces were then subjected to a lamination process reminiscent to that used in the production of plywood.

Illustration 52 The laser cutting process of the veneer sheets.

Illustration 53 The grain fiber direction of wood veneer relative to its bending direction.

The Lamination Process:

Illustration 54 The lamination process and its necessary tools and parts: vacuum press, mold and veneer cutouts.

The lamination process required to create a single scale begins with two veneer pieces like the ones described above. An even layer of glue is rolled onto the surface of one veneer piece, while the other piece is placed on top of the first (ill.55). In both layers, the direction of the wood fibers run parallel to one another. The two layers are then positioned on top of the mold and are ready to be laminated (ill.56). In order to properly laminate the pieces of wood veneer against the complex form of the mold, a vacuum bag press was developed and constructed. Vacuum bag lamination is a clamping method that uses atmospheric pressure to hold the adhesive-coated components together in place until the adhesive cures (ill.57). When the air is removed from the sealed bag, a vacuum is created. The resulting pressure applies a uniform load onto the veneer pieces which form themselves against the mold within the bag. Another benefit to using this method is that while air is drawn out of the vacuum, air also escapes the wood cells within. This allows the glue between the veneer pieces to seep into the wood cells, resulting in strong and uniform adhesion. The veneer sheets are capable of acquiring and retaining the form of the mold due to the process of lamination.

Illustration 55 Applying adhesive onto the veneer cutouts.

Illustration 56 The glued veneer cutouts, ready to be laminated together against the mold.

Illustration 57 The vacuum bag lamination process. Left: The mold is placed in the bag with the veneer sheets that are to be laminated. Right: The air is removed from the bag while the veneer sheets are pressed together against the mold in order to adopt its shape.

During the creation of this scale prototype, many iterations were fabricated using various layer ratios and veneer thicknesses in an attempt to identify which combination yielded the strongest yet most flexible results. The two-ply veneer construction, consisting of two 1mm birch veneer sheets, resulted in the highest degree of bending and overall strength for this prototype. The sine wave shape of the scale permits for bending, stretching and compression of the scale. Illustration 58 demonstrates the range of motion with which a single scale is capable of responding to external forces.

TEST SETTINGS

THICKNESS: 2 MM (3PLY VENEER)
WIDTH: 32 MM
LENGTH: 500 MM

Illustration 58 Investigating the malleable properties of the laminated scale.

Once multiple scales were created, their behaviour was analyzed as a collective assembly. Like the overlapping composition of shark and fish scales, the laminated scales were then arranged onto the substructure in a similar fashion (ill.59).

Due to the tapered geometry of the scales, this process was facilitated by fitting one scale's narrow profile into the following scale's broader profile. This created a tight fitting scaled pattern that could repel elements like rain or snow. This simple model demonstrate a manner in which multiple veneer scales could behave as a unified system once assembled to a flexible substructure beneath (ill.60).

Illustration 59 A prototype model assembly comprised of several scales arranged across a substructure.

Illustration 60 The bending behaviour of the scale and substructure assembly.

The design of these scales and the explorations conducted established that the malleable skin could achieve a number of deformations in response to the deformations of the substructure. Indeed, this system reflects the behaviours and strategies used by nature in its various application of scales in biological species where movement is essential.

These initial explorations served as early prototypes from which a more developed system would later arise. Such explorations were crucial to the continued understanding of capabilities of plywood and veneer, as they also aided in establishing certain fabrication techniques and methodologies from which the next phase of the research would develop. The next challenge required that all previous findings from the structure and skin explorations would be combined for the purpose of designing a homogenous assembly that performs as a comprehensive system.

4 Chapter: Proposed System

The aim of this investigative proposal is to develop a plywood lattice structure that exhibits innovation in terms of its construction, performance and capabilities. The prototypes outlined in this section are the product of four major objectives:

1. To develop a lightweight plywood system that functions as a membrane structure capable of achieving complex geometries from an initially planar form;
2. To develop a structure whose overall form results from the interconnected behavioral properties of the assembled elements, and whose form is self-sustaining due to these same behaviours;
3. To develop an active lightweight structural system that combines structure and skin into one cohesive assembly;
4. To incorporate an integral design approach that shifts away from pre-conceiving a form, instead towards employing the behavioural patterns and capacities of a material in order to guide the self-organizing properties of the system.

4.1 The Development of the Proposed System.

4.1.1 Prototype for an Active Bending Lattice (Structure Prototype #2)

The proposed lightweight structure, to be presented can be described as a variable grid lattice structure. This is due to the fact that the system is made up of malleable laths, arranged in a lattice grid pattern capable of adopting into various forms while maintaining structural integrity. The lattice is composed of laths with upper and lower chords (ill.61). The two chords are made of veneer wood strips which have been drilled and laser cut to equal lengths.

Illustration 61 Top: The sine curve geometry of the lath. Middle: The two chord sections of the lath. Bottom: The overall composition of lath components.

Like the design of the lath which was presented in section 3.2.1, this lath is designed in a way that resembles a truss. This arrangement allowed the malleable veneer strips to garner significant amounts of strength and stability. The lath assembly consists of three wood strips that are connected by spacer elements which are, in this version, threaded rods (ill.61). The variable spacers can either increase or decrease the depth of the lath chords, causing the wood strips to bend, thereby changing the curvature of the flat lath assembly in one direction (ill.62).

Illustration 62 The deformation of a lath through the adjustments of the spacer elements.

The lath configuration is therefore undergoing variable transformations due to the manipulation of the spacers and the bending properties of the modules. Illustration 63 depicts the range of motion of a lath, made possible by the adjustment of the variable spacers. When a desired curvature is achieved, the spacer bolts are then tightened so that the assembly may retain its geometric configuration.

Different thicknesses of wood veneer strips were tested during the construction of this prototype in order to assess the ways in which the assembly performed using varying material thicknesses at this scale. This step was crucial towards determining the ideal ratio between flexibility and strength in a model of this size.

Illustration 63 The range of motion of a lath, made possible by the adjustment of the actuating spacers.

The developed lath assembly was then arranged in a planar square grid formation to create the lattice pattern shown in (ill.64). The laths are bolted together with the existing spacers at uniform distances of 6” in both ‘x’ and ‘y’ directions. The spacers allow the lattice grid to deform further in a “scissor-like” fashion which transforms the square formation of the assembly to a parallelogram (ill.65). This stage is particularly significant because it demonstrates that the network of laths contains more than a single degree of movement in order to achieve complex forms. Unlike a single lath, this layered and grid arrangement of laths enables bending in two directions and works together as a network in the creation of complex double curve geometries. Thus, a system capable of structural

stability and double curved formations is achieved through the behavioural properties of its elements and the process of incrementally adjusting the local spacers within the laths.

Illustration 64 A grid lattice composition comprised of several laths.

Illustration 65 The scissor-like deformation of the lattice grid.

4.1.2 Scaled Skin (Prototype #2)

The skin system developed to cover the lattice structure is composed of two scale types: a concave (cosine profile) scale and a convex (sine profile) scale. Together, the scales constitute a staggered formation across the lattice grid which provides a tight overlapping envelope (ill.66). This formation was specifically inspired by the staggered composition of fish and shark scales (as shown in chapter 3), although such patterns are indeed present in other species that employ scaling as a protective skin strategy.

Illustration 66 The “Sine” and “Cosine” scale system.

The flexible behaviour of the wood veneered scales allow them to deform and respond to the changing geometries of the lattice structure onto which they are fastened. The responsive nature of the scales is achieved in part because of the flexible nature of the material as well as its laminated wave-like form, similar to that of the lattice. Like the scale prototypes which were explored in Chapter 3, these scales were fabricated using two layers of birch veneer, laser cut into a desired shape and laminated together using a

mold and a vacuum press (ill.67). The scales were then fastened onto the threaded spacers of the lattice holding the overall assembly together.

1

2

3

4

5

6

Illustration 67 The fabrication process of the scales.

In order to allow the structural lattice to retain its ability to deform in scissor-like fashion, the scales needed to be designed in such a way as to allow this phenomenon to occur while at the same time providing a tight envelope which could repel possible external elements such as rain. The three-dimensional form of the ‘sine’ scales allows for compression and stretching of the scales in order not to restrict the structural lattice’s deforming capability (ill.68). Simultaneously, the form of the ‘cosine’ scales permits deformation of the scale in response to the changing configuration of the adjacent ‘sine’ scales. In turn, the ‘sine’ scales respond to the changing scissor-like deformation of the substructure via a slotted mechanism that is embedded in the ‘sine’ scales at one of its two connection points (ill.69). These design strategies, made possible due to the material characteristics of wood, enable the skin of the system to work in harmony with the structure. In this way, both skin and structure share similar characteristics which together, work as a network of interconnected elements.

Illustration 68 The deformation of the “Sine” scale relative to the lattice diagrid

Illustration 69 The “cosine” scale’s slotted mechanism allows for the deformation of the overall lattice diagrid.

4.1.3 1:5 The System as a Whole

Illustration 70 Illustration of the 1:5 system.

Prototypes I + II illustrate the geometric variability and structural potentials of this system at an early stage and were further developed through a larger scale model. A 4' by 4' model was constructed in order to demonstrate the relationship between structure and skin, as well as the complex forms which could be generated by this system (ill.70). The development of this model was also necessary in determining how the system would behave in three dimensions, as a whole, while supporting its own weight. The planar system was hung following its assembly, and the parameters of the spacers were adjusted in order to achieve a variety of geometric configurations (ill.71-72). The resulting structure consisted of a robust assembly, capable of forming complex geometries while withstanding compression, tension and bending forces. The structure and more specifically the scales were significant because they also provided a sense of the spatial

potential and qualities of the system. Its multifaceted composition and materiality evoke a warm and intriguing experiential quality. Furthermore, the laminated scales allow light to permeate through the assembly, giving the possible inhabitable space a warm glow from above. Other scales were laminated using veneer with a thick paper backing which prevented light from transmitting through the scales. This was important as a way to determine how one might choose to control the amount of light entering into the space (ill.73).

Illustration 71 Geometric deformations of the 1:5 system.

Illustration 72 Further explorations of the geometric deformations made possible using the 1:5 system.

Illustration 73 Views of the underside of the system showing the transmission of light through the assembly.

System Installation

After the completion of this previous model, a larger model needed to be constructed in order to further explore the geometric and structural potentials of the system over a larger surface area. As a result a 5' by 12' installation was constructed to test the system and its behaviours at an identical scale to the 1:5 system. For this installation, the lath strips were laminated using three layers of poly-birch veneer which constitutes a thicker veneer. This was used to satisfy the additional strength required for an installation of this size. The process of laminating the strips into its pre-stressed concave and convex forms required a molding process. The strips were laminated in a similar fashion as the scales described previously (ill.74). The lamination added significant strength to the strips while still allowing them to remain flexible. The pre-stressed strips also allowed for easier assembly as their forms were already shaped into position and thus ready to receive the spacers. Once all of the strips were laminated, the installation was assembled as a flat assembly into a grid lattice (ill.75). Following this, the model was manipulated incrementally through the adjustment of each individual spacer element into its approximate overall form whilst still on the ground (ill.76). The installation was then suspended and further manipulated into its final geometrical composition (ill.77). Because of its increased size, the installation allowed for the exploration of more complex double curved geometries. It also demonstrated the strength of the system and its interesting formal and structural properties as a whole.

Illustration 74 The fabrication process of the large final installation.

Illustration 75 The planar assembly of the large final installation.

Illustration 76 A time lapse demonstrating the geometrical manipulation of the system whilst on the ground.

Illustration 77 Illustrations of the final installation, hung at Carleton University.

Illustration 78 Close up details of the final installation.

4.1.4 System Structural Properties

The lattice's ability to achieve and maintain double curve deformations enables it to function, conceptually, as a grid shell membrane. Due to its adjustable properties, the lattice is able to function in ways similar to a planar space structure, a suspended lightweight tensile net and a compression shell or dome (ill.79). This can be seen in the ability of the system to form such geometric configurations as paraboloids or barrel vaults, characterized as saddle shapes associated with tensile and shell structures. The ability of the system to function as a tensile surface structure or a shell structure implies that it can serve more than a single application: the system can be suspended using cables and poles like a tent or grounded using footings, or employing a combination of the two. These are expanded in the next section.

Illustration 79 Diagram illustrating the compressive and tensile behaviours of structures.

Applications

Suspended Structure:

In a tensile application, the initially planar arrangement of the lattice can be manipulated in order to allow a response to the tensile forces at play. In order to avoid buckling and high amounts of stress, the bending structural elements, functioning in tension, must be adjusted to control the uniformly tributed load acting on them. Therefore, the system must be capable of changing its form in the direction of the forces in order to allow its members to achieve a state of equilibrium between the tensile forces and the pull of gravity. This property of the overall system can be easily understood and modeled by hanging chains. When a linked chain is suspended between two points, it adopts a curved shape under the uniform load distribution of its weight and the pull of gravity. The curvature obtained by such a self-shaping structure is called a “catenary” (ill.80).

Illustration 80 Diagram illustrating the suspended system behaving in tension.

Grounded Structure (In Compression):

In a self-supporting application, the lattice can modify its initially planar geometry as it performs in compression. To achieve such configurations as arches or domes, the system can once again be adjusted using its variable parameters. Structural stability is achieved across the system due to its ability to maintain or stiffen its individual elements in order to cope with compressive forces. Additionally, structural stability and equilibrium are achieved through the overall compressive form of the system working in collaboration with the fixed spacers and its grounded support points. The self-organizing catenary obtained from the hanging chains can once again be used to determine the optimal forms in compression. In a suspended chain, only tensile forces are at work. However, by inverting the catenary obtained through this tensile configuration, one acquires stress line that is only in compression (ill.81). Antoni Gaudi was one of the first architects to apply this technique in the design of arched domes and vaults, (i.e., In the Sagrada Familia⁴⁸). This technique can be employed in the discovery of similar complex shape and forms by using the proposed system (ill.82).

⁴⁸ Frei Otto and Bofo Rasch 1996 pg.155

Illustration 81 Diagram illustrating the system behaving in compression.

Illustration 82 Antoni Gaudi's (Sagrada Familia) suspended chain models.

Hybrid Structure (In Both Tension and Compression):

In a hybrid application of the system, the assembly is capable of performing in both compression and tension. Once again, in order to cope with these forces, the system is adjusted and allowed to modify its geometric configuration, in response to the applied stresses. This can be seen in examples of double-curved shell structures, in which both tensile and compressive forces are at work (ill.83). This hybrid behaviour of the lattice can allow for applications such as a canopy for a stadium or a theater where part of the structure can be grounded and the other can be suspended to remain open.

Illustration 83 Diagram illustrating the system behaving in both tension and compression.

4.2 The Development of the 1:1 System:

In order to realize the potential of this system and assess its feasibility, it was necessary to verify its performance at a 1:1 scale. The challenge associated with this step was to enlarge the scale of the prototype while preserving its structural and malleable properties. Furthermore, this 1:1 construction needed to be completed using only the materials and resources readily available. This meant that all plywood and veneer needed to be cut from 5'x 5' plywood, 4' x 8' veneer sheets. The second challenge involved the development of construction details that would allow the system to properly function at full scale.

The Full Scale Structure:

In the small scale prototype model presented in section (4.1.1), the strips making up the top and bottom chords of the lath were made up of continuous veneer pieces. At full scale, three-ply plywood was used to create these strips, despite the fact that plywood sheets are only available in finite lengths of 5'. Therefore, in order to create a continuous strip, a single strip of plywood was insufficient. Instead, a technique was developed which reduced these strips to a multitude of single, pre-stressed components that could be linked together to make up the entire structure (ill.84).

Illustration 84 A single pre-stressed lath component at a 1:1 scale.

The curved components used in the prototype strips in (section 4.1.1) were further analyzed with the help of digital modeling software. This step allowed for fine tuning of the forms due to the thickness differentiation of the larger 1:1 scale. The digital model also allowed for components to be fabricated accurately with the use of a mold constructed using a CNC router.

In order to fabricate these components, 5'x5' plywood strips were cut across the fiber grain direction into 4" wide strips. Two strips were then laminated together and draped across the mold in order to create the bendable, pre-stressed curved components. The components were then drilled at both ends and at the center in order to accommodate the spacers that would facilitate the joining of multiple components. The form of these pre-stressed laminated components allows them to function similar to the scales that were presented earlier. The curved components can cope with both compressive, tensile and bending forces due to their form and material properties. Furthermore, the lamination technique provides the elements with a very strong, yet flexible material property. Again, as in the prototypes previously explored, multiple iterations were fabricated and investigated using different ply layers in order to identify the combination that yielded the strongest and most flexible results.

Illustration 85 The lamination process for a single lath component at a 1:1 scale.

The Skin at Full Scale:

The fabrication process for the scalar skin system at the full scale followed the same procedure used for the structure. The two scale types forming the skin required that they be analyzed using the same digital modeling software in order to be appropriately fabricated at the larger scale with molds. Because of the size limitations of the CNC machine and the required dimensions for an appropriate mold at this scale, it was not possible to mill the mold from a single block of wood. Instead, the mold was constructed with wooden ribs and glued to a base. This ribbed structure was then covered with 2 sheets of three-ply plywood providing a smooth surface for lamination (ill.86).

Illustration 86 The development of the 1:1 mold.

Subsequently, veneer sheets measuring 2mm thick and 4'x8' long were selected to construct the scales. A thicker veneer than that used in the small-scale prototypes was necessary due to the added structural rigidity. Cut-out veneer units were then stacked in pairs and laminated across the full-scale and vacuum formed. When installed onto the assembled substructure, the scalar unit did not possess adequate structural stiffness for to the increased size. The units were revised using three layers of 2 mm birch veneer to provide adequate strength and stability.

The following images illustrate the fabrication process described above:

Illustration 87 (CNC) machine cutting the veneer sheets prior to the lamination process.

Illustration 88 Preparing the vacuum press and the mold for the lamination of a 1:1 scale.

Illustration 89 The application of adhesive onto the veneer sheet cutouts.

Illustration 90 Left: Placing glued veneers into the vacuum bag on top of the mold. Right: Removing the air from the vacuum tight bag.

Illustration 91 The assembly process of the system at a 1:1 scale.

Illustration 92 The completed system assembly at a 1:1 scale.

The techniques and methodologies incorporated in the development of the system at full scales established that it can be constructed using three primary components: the lath component, the scalar skin units, and the connection spacers. The development of this model further demonstrated that the system still retained its bending and structural properties at this 1:1 scale (ill.93). The manufacturing process of this system when automated, could be extremely efficient in material use and completion time. Equally as efficient would be the transportation and assembly due to the simplicity of the design and its parts. It is important to note that although the system is made up of individual components, its overall structural behaviour is the result of the interconnected components working as a holistic network. This also prevents the structure from collapsing due to the failure of a single or several components. This also allows the system to be easily repaired by isolating and replacing components, should one fail.

Illustration 93 The bending properties of the system illustrated at a 1:1 scale.

4.3 Structural Details

4.3.1 Proposed Actuation Spacer Units

The adjustable spacers are one of the most fundamental components of the system given their ability to adjust the geometric configuration of the assembly. In prototype #2 and the full scale model, the spacers consisted of simple threaded rods fastened with nuts and washers which could be adjusted along the length of the rods to modify the depths of the system's chords. In the full scale model, the threaded rods proved to be an appropriate way of modifying the settings of the structure. However, should this system ever be manufactured, this detail requires further development regarding strength, functionality, adjustability and practicality.

The developed design for the spacer units consists of a three-part adjustable cylindrical element bearing two ball joints at each end. In concept, the spacer works like a hydraulic cylinder which can retract or contract in order to change the chord depths as required in the system. The ball joints at either ends of the spacer elements allow for necessary rotation to take place in order to relieve the spacer unit from bending stresses that occur during the deformation of the lath geometry. Unlike the threaded rod employed in the built prototypes, in which the nuts were adjusted manually, this design allows for easy adjustments to occur by simply pulling or pushing the cylinders to the desired length. The spacer's three part assembly also contains a tooth-like pattern inside, and a ratchet mechanism used for locking the spacer in place (similar to a "zip-tie").

Furthermore, if such a system were to be developed further, through computational building information modeling (BIM) software, then the structure would have the potential of becoming a kinetic structure. If the spacers were to be developed as an

automated hydraulic system controlled by an (BIM) interface, the structural system would have the capacity to be highly controlled and adjusted. This can allow the system to open up or close to create a canopy depending on the time of day or weather.

Illustration 94 A spacer element.

Illustration 95 Spacer element details.

Illustration 96 Details illustrating the adjustability and range of motion of a spacer element.

4.3.2 Connection Details

The multiple forces acting upon this dynamic lightweight structure are most prominent at connection details. As a result, the success of the design as a whole is also dependent on the specific details of these connections. Given the malleable nature of the system, structural connections were developed to withstand the tensile, compressive and bending forces acting upon them. Furthermore, connections were uniquely designed using an integrated approach that would ensure proper overall functionality throughout the system. Several of these primary connection details required for the system to perform in such a way in different applications are illustrated below.

Grounded + Wall Connections:

To properly secure this system at a support location such as a wall or a footing, the connections needed to be strong yet flexible in order to cope with the overall adjustability of the structure. This needs to be similarly integrated into the overall system to perform harmoniously.

The connection consists of a two-part design that pivots at a common node. Part A would be anchored to the end of a lath at a spacer location, allowing the lath to pivot from side to side. Part B would be anchored to a footing, wall or ceiling. Part A+B come together at a node where they are permitted to pivot around a pin connection (ill.97). Together, the two pivot points of the connection detail allow lathes of the system to be fastened to a support point at a variety of angles (ill.98).

Illustration 97 Connection details to walls, ceilings and footings.

Illustration 98 Connection pivot points illustrating the range of motion made possible.

Illustration 99 3D visualization of the connections to a vertical or horizontal surface.

Illustration 100 3D visualization of the connections anchored to footings.

Illustration 101 3D visualization of the system and the connections anchored to walls.

Cable connections:

In order to provide the possibility for the system to incorporate support cables, specific connection details were designed. The first detail would connect cables directly to the spacers to provide support for the structure. This connection would occur at the top of the spacers, above the skin surface. This detail would provide two degrees of rotation, allowing the cables to be connected to virtually any support point (wall, ceiling, pole) located at various angles (ill.104). The second detail functions in concept like the two-part connection presented in the previous section. The difference being that part B is now replaced with a cable end link connection (ill.106). These details would be required for a suspended scenario in which cables are used to provide support for the system. Illustration 107 demonstrates two scenarios in which both cable and ground connections are required to provide support for the system.

Illustration 102 A spacer cable connection.

Illustration 103 Spacer cable connection detail.

Illustration 104 Degrees of rotation made possible via the spacer cable connection.

Illustration 105 Exploded detail of the spacer link, cable end link and the cable wall connection.

Illustration 106 Cable connection #2.

Illustration 107 Two scenarios in which both cable and ground connections are used to support the system.

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Illustration 108 Enlarged details corresponding to Ill. 100.

4.4 Lessons Learned and Future Considerations

Many of the valuable lessons that emerged from this research concerned the importance of prototyping. It was primarily through physical and material investigations that many of the design challenges involved were overcome. On several occasions, prototypes were fabricated as a means of determining or confirming notions surrounding material properties, limitations and opportunities. These discoveries, which have been presented throughout this paper, then paved the way for the next series of steps required by the design development process.

There were, however, certain challenges that can only be properly identified and undertaken through further research and development. Naturally, the work that was conducted as part of this research was restricted to certain factors such as time, budget, resources, available tools and material properties. The digital fabrication tools used in the creation of various models and prototypes were limited in terms of their capabilities and size restrictions. As a result, all of the physical explorations were required to fit within the size constraints and physical limitations of these tools over the course of the design process.

However, the area which would most likely benefit from the highest amount of continued research and development concerns the digital analytic software available during this time. The digital modeling software that was employed during this project was used solely for the purposes of visual analysis, and for increased precision when fabricating and duplicating the forms discovered via physical exploration. In this way, the digital tools were crucial to the fabrication stages of the research. It was possible to digitally

model the proposed structural system and all of its detail components under static conditions, prior to construction. However, it was not possible to create a digital model that could respond to third party inputs or circumstances in the same way that a physical model could. In other words, the conventional digital modeling software that is available today is limited in terms of incorporating factors such as material properties, constraints and behaviours into an actively responsive digital model. Therefore, there's yet to be a way for designers to explore a variety of scenarios involving material-based design by merely using conventional digital software. This is why the physical and material investigations presented in this project were so imperative to the design development of an active lightweight, material-informed structural system. Unfortunately, the perpetual fabrication of physical models presents its own set of challenges. Given the available resources, physical models can only be built to a certain size and scale, which can in turn limit findings. The construction of models and prototypes also takes time and money, which could be otherwise better distributed if certain analytical software were eventually developed.

In order to fully explore the spatial, structural and formal behaviours of the system within the digital realm, it is very likely that custom computational software would be required. The conventional modeling software available today such as BIM, CAD, or parametric software like Rhino and Grasshopper are simply incapable of modeling the complex behaviours of the proposed system. The development of a digital parametric design software that can incorporate material properties and complex behavioural patterns is critical for the development of the proposed system in this research, as it is truly the only way to further push the proposal's potential in terms of form-finding, spatial exploration

and structural analysis. Furthermore, such tools would permit designers to virtually evaluate the feasibility and performance of this structural system in almost any given scenario or application. For example, one could study a simulated instance of the system applied as a pavilion in a specified site. It is very likely that such digital advancements can only be made possible through the collaboration of interdisciplinary professionals including architects, engineers, programmers and software developers. Once these developmental stages have been achieved one can imagine this system being used in a variety of applications. Because it is lightweight, easy to assembly and relatively strong, the system can be used for long span shell structures housing a variety of functions such as stadium venues, outdoor amphitheaters and even temporary (or travelling) public exhibitions. Finally, the system can be applied as a canopy either in a standalone self-supporting manor or used in combination with an existing structure to create shelter or partial enclosures.

Conclusion

The focus of this research was to investigate and explore the possibilities resulting from an integrated design approach in which material, form and structure are inherently linked. In today's building industry, the architectural design process is predominantly based on hierarchical design methodologies that prioritize the generation of form over material information. These practices contradict the notions associated with material-informed design which propose that a material's innate characteristics and capabilities should be explored and seriously considered at a very early stage of the design process. By adopting these approaches, one can quickly come to recognize the benefits of allowing the properties and behaviours of a material to serve as driving agents for design.

The presented research predicted and demonstrated that the development of integrated design processes that work in concert with material information can in fact unearth novel opportunities for design, concerning even seemingly familiar materials. Based on these approaches, the research presented herein was capable of illustrating that wood, more specifically plywood, could be further explored in terms of its application as a high-performance, composite structural material. While it is one of the oldest construction materials known to humankind, wood is also a renewable, energy efficient and fully-recyclable resource. By integrating plywood's natural properties and innate behaviours with holistic design and fabrication methodologies, a number of physical and digital investigations were conducted with the aim of producing a design for a lightweight, self-sustaining structural system. The results of this venture proved to be surprising, yet effective.

Via the methodologies and explorations presented in this research, it was established that an integrative design approach that employed plywood as a primary material could very well lead to the creation of an active, lightweight construction assembly. That being said, a number of the techniques used in the fabrication of such a system were put to rigorous tests in order to determine the most optimal and harmonious methods of constructing this assembly. It was discovered that ancient lamination techniques in combination with digital fabrication tools proved to be most successful over the course of this task. Using various built prototypes and proposal models, the potential and performance capabilities of the system were studied. Both structural and architectural potentials of this material were discovered and tested by means of fabricating multiple models of the system at a variety of scales. Furthermore, the findings confirmed that plywood's highly unique bending and elastic properties could undeniably provide unprecedented benefits to applications outside of the traditional wood-based products commonly used in today's construction industry.

The research and investigations presented as part of this thesis are to be understood as the initial development stages of a much larger area of research. At this time, the system has been developed to a point in which it is both functional and attainable. However, the findings that have emerged from this undertaking may benefit from further experiments and collaborative, inter-disciplinary research as was done by the team lead by Achim Menges for the ICD/ITKE Research Pavilion. Further areas of development would seek to identify more efficient means of manufacturing the materials required for this system. Concurrently, they would attempt to further develop digital simulation tools for effective use in better predicting and comprehending the behaviours of timber products in specific

applications. This will allow for higher levels of precision to be achieved during the integration of exploration and design phases. Finally, should one wish to fully analyze this structural system under its intended uses, it would be highly advantageous that a large scale, architectural design application such as a pavilion, be constructed and studied.

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