Rethinking of timber joinery in 21st-century architecture
The computation of a timber joinery through complex geometry

By

Maryam Ali

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Brian Lee

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Abstract

In recent years, there has been a renewed interest in timber joinery in contemporary architecture. With the introduction of digital fabrication technologies and computational design, it is now possible to create complex timber structures with more complex shapes and designs. One of the critical advantages of timber as a building material is its ability to be combined in various ways. Timber joinery can create solid and durable connections between structural members while providing an aesthetically pleasing finish. In the 21st century, architects and designers are exploring new ways to use timber joinery to create unique and innovative structures. Computational design tools allow designers to create complex geometries that can be fabricated precisely using computer numerical control (CNC) machines and other digital fabrication technologies. Designers who are well-versed in programs like Rhino, Grasshopper, or Revit have the ability to utilize parametric modeling software that can calculate timber joinery that is based on intricate geometry. These tools allow designers to create 3D models of the structure and conduct experiments with different joinery options and configurations. Once the joinery is designed, it can be fabricated using CNC machines or other digital fabrication tools. It allows for high precision and accuracy in the fabrication process, ensuring the joint perfectly fits together. The use of complex timber joinery in contemporary architecture provides functional benefits and a unique aesthetic that cannot be achieved with other materials. By rethinking traditional joinery techniques and embracing digital technologies, architects and designers can create structures that push the boundaries of what is possible through timber construction. This thesis will investigate and explore the timber joinery system and fabrication methods, one of the old wooden structure techniques used in the age of digital technologies that rejuvenate the usage of conventional construction processes in timber buildings. The main aim of this thesis was to study computational

design in creating complex wooden segmental base structures that rely on interlocking timber joints as the primary form of connection. This involved analyzing the role of wooden joinery and exploring complex systems made using this technique.

The second objective was to create a digital model of several types of parametric wood joineries, such as halve and lap joint, Tenon and mortise joint, and finger joints. A digital model of a complex segmental plate structure with three fundamental parametric joints was also developed. The three basic types include finger, halve and lap clip, and Mortise and Tenon joints. The third objective is a structural and shape optimization of the basic mesh for specified complex geometry, which will be a digital model to evaluate the applicability of the generated joints, and will be determined because of this investigation.

Table of Contents

List of Figures

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Through my research and graduate program, many people have played an instrumental role in my success and achievements. I wish to show my gratitude to all of them. However, primarily, I must acknowledge my limitless thanks to Allah, the Ever Magnificent, the Ever Thankful, for His help and blessing. I am sure this work would only have come true with His guidance.

Words cannot express the amount of gratitude I have in my heart for my family, who raised me to be curious. This thesis exposed with them nourishing my curiosity daily. Furthermore credibly grateful to the Fulbright program for giving me a lifetime opportunity to sharpen my skills and explore myself in architecture and the architecture field.

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Thank you all.

Dedication

This thesis is dedicated to the following:

Allah Almighty, my Creator, and my Master,

Prophet Mohammed (Peace be upon him), who taught us the purpose of life,

My loving Parents, who have helped me through the path of knowledge,

My beloved Brothers, who stand by me when things look bleak

Chapter 1

1.1 Introduction

In recent years, there has been a significant demand for renewable and sustainable resources in the construction sector, resulting in a resurgence of interest in timber as a building material. (Nabaei and Weinand 2011). Nature has immense potential for increasing human productivity and sparking future technology, especially in architecture and construction. (Xie et al., 2019). Timber is one of the oldest primary building materials used for centuries across the globe. Over time, equipment and procedures for cutting, joining, and constructing timber constructions have evolved. Because of its durability, robustness, and high-performance level against heat and sound, wood possesses advantages that make sustainable and cost-effective construction possible. Furthermore, the development of engineered wood products has been aided by progress in manufacturing techniques and adhesives. These factors, coupled with an increased focus on sustainability and performance-based design, have made wood an obvious choice for digital architectural fabrication.

The digital age of the 21st century has witnessed the use of technology that has driven a novel approach to architectural design. We are in the fourth industrial revolution, and digital technology and fabrication tools have the potential to revolutionize the way we think about architecture dramatically, especially in the material craft (Turner 2021). In the past decade, there has been a change in digital architecture that emphasizes production methods and material-based approaches rather than merely focusing on form, geometry, and representation. Consequently, architects can now incorporate previously unavailable fabrication processes and material systems into their design process. (Gazit 2016).

Contemporary computational technologies make it possible to create intricate surface shapes that correspond to the complexity of the design problem and surpass Euclidean geometries to embrace more unconventional topological geometries. In architecture, utilizing computational technologies for design and manufacturing has witnessed a significant surge since the 2000s. This has led to the integration of the design and fabrication processes, where the feasibility of a design proposal is simulated, assessed, and verified during the initial design stages. Laser machines, CNC machines, and robots are just a few of the technologies fueling the development of novel approaches for designing and fabricating complicated wood structures. The capacity to digitally execute the real-time simulation, assessment, and design constructability testing at the early design stage resulted in faster design production. (Estateyieh 2017). Timber joints as an ancient as 7000 years have been discovered in early wood architectural remnants. Before the industrial revolution, the most fashionable way of joining timber parts was through various techniques developed by carpenters. These techniques were used to increase the length of components for longer spans, like roof framing and bridge trusses, or to increase the breadth of elements for broader coverage, such as stacked walls and roof cladding. Over time, carpenters developed various joining techniques suitable for different circumstances. However, with the widespread use of mass-produced metallic connectors like screws and bolts and the increased labor costs in developed countries, construction companies have gradually abandoned timber joints in favor of cheaper and more efficient automated practices. (Rogeau, Latteur, and Weinand 2021) Nowadays, most constructions are planned and constructed using computational techniques. The integration of advanced technologies, such as digital tools and manufacturing processes, is fundamentally transforming the field of architecture and construction. (Silva 2019). Throughout history, the evolution of modern design and production has resulted in a shift from integrating material knowledge and form-making into a single process towards compartmentalization. This means that form-making is now viewed as an independent process. This differs from traditional craft production, where the material and form are naturally intertwined as part of a making tradition. (Oxman 2010)

1.2 Problem Statement

The world is facing global warming. Furthermore, construction plays a crucial role in it. The construction industry contributes to scale and shares in developing countries worldwide. As the sector increases, so does the potential for increased pollution and waste. Based on research, the construction, and built environment are responsible for 40% of the world's greenhouse gas emissions. However, due to changes in energy usage patterns, CO_2 emissions from building operations decreased by 10% in 2020 to 8.7 gigatons, down from about 9.6 gigatons in 2019. Additionally, energy emissions related to building materials manufacturing decreased from 3.6 gigatons of CO_2 in 2019 to 3.2 gigatons in 2020 due to a new construction decline. Despite these reductions, the global contribution of energy-related CO_2 emissions from buildings and structures compared to other sectors is expected to be 37% in 2020, down from 38% in 2019 due to sectoral movements. As part of efforts to reduce emissions, there is a commitment to decrease emissions from brick production by 44% (1.799 million tons of CO_2 equivalent) by 2030. (Environment 2021) Climate changes profoundly impact the building envelopes primarily because of the materials used, as these also absorb the CO_2 and other factors from the surrounding. This strongly emphasizes eco-friendly materials that can create a technologically independent, carbon-negative building façade. The architects are responsible for the building's design, construction, enlargement, conservation, restoration, or alteration, including technical and conceptual drawings. The Alberta Architects Act defines" no sharp distinction from material engagement in architecture practice". (Walker 2021) The primary research objective involves identifying the gap in wood architecture and utilizing digital fabrication to develop innovative designs for wooden joinery that can be used in future constructions. Consequently, there are compelling reasons to anticipate that timber, which has been a primary construction material for centuries, will assume even greater significance in sustainable construction methods in the future. "As a result, there are many substantial reasons to believe that timber, as one of the world's oldest building materials, will become even more essential as a sustainable construction material in the future. (Jeska, Khaled Saleh Pascha, and Rainer Hascher 2015) In recent years the research on advanced wood architecture has been under focus in more than one area, for example, timber high-rise buildings and towers, massive timber construction, timber building systems, and advanced fabrication. The research will specifically focus on "timber joinery," an interlocking wood-to-wood connection, an essential and fundamental aspect of timber construction until the 19th century; after that, it was replaced by mechanical and chemical bonds like nails and nail adhesives.

The research investigates using digital technologies to support Timber joinery in various timber components, such as frame, plate/panel/board members, or shell structures. It aims to explore how computational design techniques like the Grasshopper and Rhino and digital fabrication techniques like CNC Milling or 3d Printing can transform conventional forms of wood joinery and establish parametric wood joinery details, with a particular emphasis on rigid interlocking wooden joints and elastic joints in complex wooden structures.

The research problem is the lack of research and investigation on the application of joints in complex wooden structures compared to the literature on rigid and elastic segmental plate joints. The research plan will address the issue by investigating how digital technologies and Fabrication method like CNC can support the development of timber joints in complex wooden structures.

1.3 The Objective

Design in complex wooden structures design with interlocking wood joinery, creating a digital model from parametric wood joineries, and optimizing the basic Mesh for specified complex geometry. Here are some potential steps taken to achieve these objectives:

- **Research Wooden Joinery:** To investigate wooden joinery, review existing literature and research on the topic, study traditional timber joinery techniques, and analyze their advantages and limitations. This will provide a foundational understanding of the subject and help identify areas where computational design can enhance the process.
- **Study Computational Design:** After the grasping of wooden joinery, it develop into a computational method and explore how it can be used to design complex wooden structures with interlocking wood joinery. This could examine various software and tools available for planning and modeling wooden joinery and compare their features and capabilities.
- **Conduct Case Study Exploration:** To gain a deeper understanding of wooden joinery in practice, the research explores a complex wooden structure that uses interlocking wood joinery as the primary connection type. It analyzes the design process and construction techniques used in the project and identifies areas where computational design could have been used to enhance the process.
- **Create Digital Models:** Using the insights gained from the research and case study exploration, the next step is to create digital models for parametric wood joineries like Tenon and mortise finger joints. The research also optimizes the form of the digital model, finding the basic form digitally for a complex segmental plate structure with parametric joints using the three basic types: finger, clip joint, and mortise and Tenon.

- **Optimize the Mesh:** Finally, the research performs structural optimization using the Grasshopper plugin on the basic Mesh for specified complex geometry to evaluate the applicability of the generated joints. This will help determine the most suitable joint types for wooden structures and inform future design and construction processes.
- **Fabrication:** One design is selected from two of the chosen case studies. It uses the fabrication technique Of CNC milling three axes to translate the digital design into physical and study how with the simple 3axis CNC, it is possible to create a complex compound design.

1.4 Significance of the Study

The research will significantly enhance the understanding of timber joinery and its application in complex wooden constructions, specifically in digital design and geometry curvature. By focusing on wood joinery and exploring how digital technologies can support its design and production, the study could provide insights into how ancient building methods can be revived and applied in a modern, digital context.

Furthermore, the research will help bridge the gap between traditional artistry and advanced technologies in the construction industry, highlighting the importance of combining the skills and knowledge of artisans with the capabilities of digital tools and techniques.

The study can provide fresh insights into the construction and manufacturing of wooden buildings, which may aid in developing eco-friendly and innovative building techniques. Additionally, this study is significant as it examines the correlation between straightforward fabrication techniques and intricate designs.

Chapter 2 Literature Review

2.1 Wood and Architecture

Wood is one of the most used construction materials used in architecture around the globe, because of its unique property and widely available and renewable resources, wood has regained popularity in construction and building materials during the last few decades. It also has a low embodied energy and a positive carbon footprint. (Krieg and Menges 2013). It has evolved from a natural resource to a modern industrial product. In architecture, a wealth of previous literature is highlighted in construction. Wood is uniquely positioned as a raw, eco-friendly, lightweight, strong, and flexible material (Chilton and İhsan Mungan, 2009). In the construction industry, there has been a recent resurgence in using wood as a building material due to the need to use renewable and sustainable resources. (Nabaei and Weinand 2011). Wood construction has different techniques, but the joinery system is the most famous. The wood-to-wood connection was a very ancient technique. The joinery has diverse types, and each one has its unique property. Wood joinery has become a highly debated topic due to advances in innovative technology. As a result of these advancements, the study of joinery in architecture has revived traditional practices in a modern manner.

Building systems are divided into two groups in an introductory survey of the history of wood construction. The first group includes traditional wood building methods such as log, timber, and light frame construction. In contrast, the second category comprises modern construction systems such as panel construction, frame construction, and solid timber construction. These are the primary systems independent of geographic location; nevertheless, differences in their application may arise depending on the country, area, and kind of building. (Kolb et al., 2008).

2.2 Building Systems in Timber Construction

From a technical standpoint, the composition and organization of the layers in a building envelope characterize how it is built using timber. Additionally, the load-bearing systems and timber construction methods have undergone a reorientation. Timber construction is a concept that has been introduced previously. For almost 7,000 years, we have been constructing them. They cut mortise and Tenon joints in timbers to link them together from when Neolithic people first learned to use sharp bronze tools. These early ancient timber constructions were primitive cottages and hovels with little aesthetic appeal. We often see ancient Rome as a marble metropolis, but it was a wooden city with only a few stone public structures. The Romans were expert builders who refined the art of constructing wooden constructions. They polished the rudimentary carpentry skills of the Greeks and their ancestors into a functional, structural system with precise artisanship. (Destefano 2020)

2.3 The basic building systems are:

- **Log Construction**

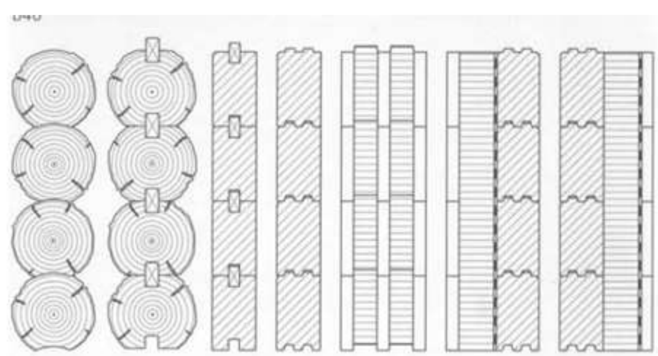


Figure 1 Log Construction Joinery

Log construction is one of the ancient timber constructions. During the early bronze and iron periods, log buildings evolved along with the development of tools. Logs, whether they are natural or manufactured, are arranged in a stacked formation to construct a wall. These logs are interconnected by being shaped into interlocking connections. (Forest Products Laboratory, 1999) In its traditional form, the log construction technique can now only be found in a few structures. (Kolb et al., 2008). The vast amount of wood required and the high degree of sag of the horizontally oriented elements are two characteristics of a log building. Mortise and Tenon couplings between horizontal trunks are standard timber construction connectors. (Aparicio 2010)

- **Timber-Frame Construction**

Compared to log building, timber frame construction is more cost-effective. The load-bearing structure was constructed using large pieces of wood smaller than standard logs to cope with the scarcity of timber in areas with depleted forests. This technique was employed from the 12th century through the Middle Ages and into the 17th century when solid wood was the primary material for building wooden structures. Timber frame buildings during this period used interlocking joinery. Nowadays, timber frame constructions are limited to small-scale buildings with multi stories. Creating tall buildings using this method is difficult due to cost, erection, and construction difficulties. (Kolb et al., 2008). The frame members used different timber joinery to connect timber joinery to construction difficulties. (Kolb et al., 2008). The frame members used other timber joinery to join timber joinery to connect.

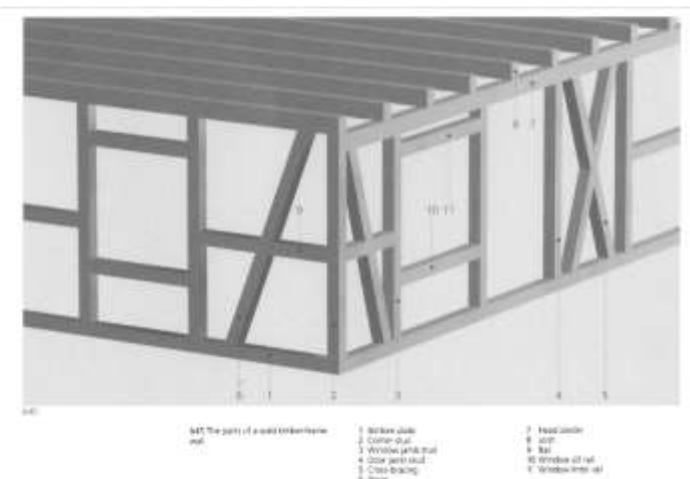


Figure 2 Frame Construction

❖ Balloon- And Platform-Frame Construction

Wooden structures were built using timber frame architecture until the 19th century. The emergence of the Industrial Revolution in the 18th and 19th centuries brought about substantial changes to the construction industry, which impacted the methods used for timber construction. Due to the introduction of new materials like iron and concrete, the capability to transport building components quickly, and the availability of low-cost fasteners and standardized timber, conventional wood frame construction was replaced by light frame architecture. (Kolb et al., 2008) (Aparicio 2010) 2010)

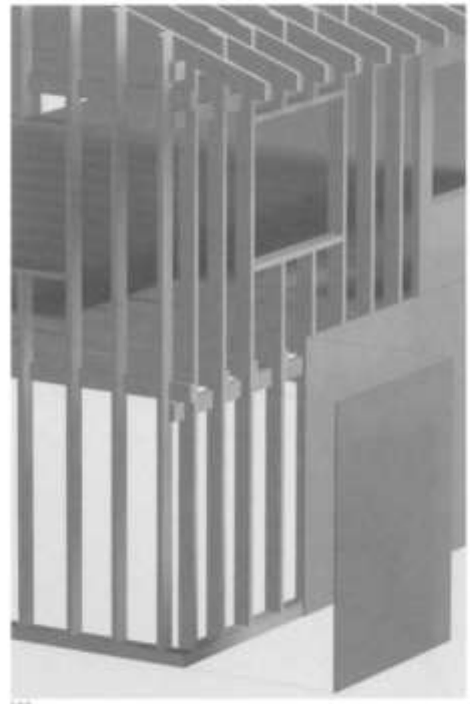


Figure 3 Balloon and Platform Frame Construction

❖ Balloon Frame

In the balloon-frame construction method, the vertical studs of the wall, known as "ribs," extend for two or more floors. These studs' top and bottom ends are created using horizontal components such as bottom plates and head binders. A flat binder is inserted into notches made in the vertical studs to support the suspended floor joists. (Kolb 2008)

❖ Platform Frame

The platform frame's distinctive feature is its built-in sections as tall as a story. This allows all trades working on the construction site to use it as a platform during the erection process. Additionally, the structure is highly adaptable in terms of design and architecture. (Kolb 2008) The platform frame's distinctive feature is its built-in sections as tall as a story. This allows all trades working on the construction site to use it as a platform during the erection process. Additionally, the structure is highly adaptable in terms of design and architecture. (Kolb 2008)

❖ Panel Construction

Panel construction emerged in the 1980s and is a contemporary version of the balloon-frame and platform-frame building techniques. Nonetheless, the components used in panel construction are more significant compared to those in balloon and platform frames. This method is primarily applied in constructing one- and two-story houses but has also been utilized in building multi-story edifices. The load-bearing structure in panel construction comprises square pieces with protecting ribs coving. The articles need precise manufacture using computer-controlled equipment. Metal and mechanical connection fasteners are used to assemble the panel structure. (Kolb et al., 2008). The load-bearing structure in panel construction comprises square pieces with protecting ribs coving. The pieces need precise manufacture using computer-controlled equipment. Metal and mechanical connection fasteners are used to assemble the panel structure. (Kolb et al., 2008)

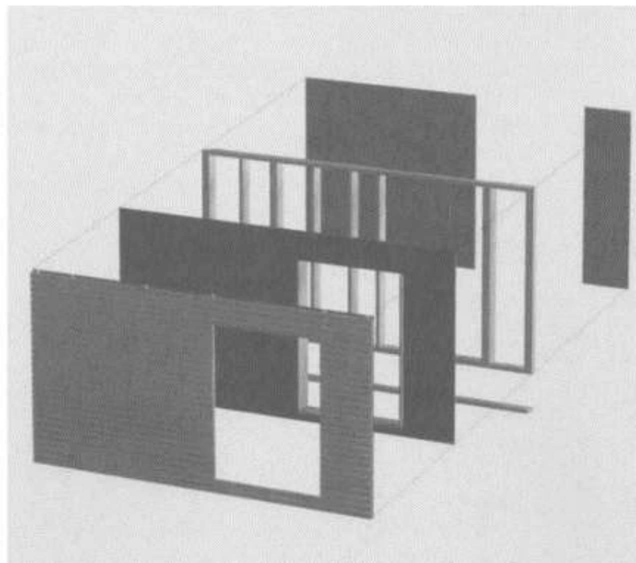


Figure 4 Panel Construction

❖ Frame Construction

Since the early days of the Renaissance, the world of timber framing has gone a long way. Timber constructions nowadays have just the tiniest similarity to ancient house and barn frameworks from previous eras. Of hewing with axes, timbers are smoothed and planned to strict tolerances. The woods are still linked with elaborately carved, interlocking joints, but the connections are no longer made like historical antecedents. (DeStefano 2020) The load-bearing framework of contemporary frame buildings comprises a widely spaced grid of columns and beams reinforced by bracing supports. This design is considered a modern adaptation of the traditional timber frame structure, thanks to the advent of new wood-based materials like glued laminated timber and connecting details. Additionally, the frame structure has evolved to incorporate interlocking wood joineries such as notched and mortise and tenon joints in columns and compound beams. Furthermore, visible connections, fasteners, and concealed steel components can also be integrated into the timber for use in frame building. (Kolb et al., 2008).

- **Solid Timber Construction**

Significant wooden planar components are utilized to construct the primary sections of the building and provide both load-bearing and enclosure functions. The weight is transferred along the edges through plate action in solid timber construction. In addition, the advancement of engineered wood products in panel form and on an industrial scale, such as plywood, has led to new building systems that rely on large-format planar wood as a load-bearing element. (Kolb et al., 2008).

2.5 Timber as a Sustainable Solution

Building with wood has grown in popularity with a growing public awareness of climate change. There is a sizable movement attempting to reintroduce wood into the construction business. It is happening worldwide, but is delayed due to our legislation and the structure of our corporate building sector. We have mostly seen small-scale experimental initiatives thus far, but wood has recently become a marketing tool for firms to sell themselves. Revolution is need the requirements for architectural contests, but we also need to learn more about the material as a profession because wood is not as safe and monitored as other construction materials used in the construction business. "Sustainability is the power to survive," says Emma de Jong 2022, who highlights the qualitative dimensions of sustainability. It is not just about quantitative values like material use and chilly bridges but about a building's ability to last through time. Buildings made of wood have warmth and honesty. It is not only an intelligent choice in calculations and renewable resources, but it is also a material that is highly valued and, as a result, can last. (Ernestrand 2017)

2.6 History and Definition of Timber Joinery

The categorization of Timber structure connection can be grouped into three primary types of joinery. The first type is chemical joinery that employs adhesives, and the second type is the wood-to-wood connection, also known as carpentry and wood joinery. According to Messler (The Essence of Materials for Engineers), He identified as "Wood joinery" as "the joining of two or more surfaces [in wood components] to produce a solid unit that fulfills a defined function." According to Mönk, as stated by Zwerger, the unique role of structural wood joints is to "join together pieces of timber permanently and firmly in such a way that the needed structural interaction of the constructional element or the construction itself is possible." (Ernestrand 2017).

Structural wood joinery serves a variety of purposes in both traditional and contemporary constructions.

- ❖ to make parts longer in both directions (splice)
- ❖ Create rigid corner connections (L- or T-shaped intersections)
- ❖ to crossover (lattice form)

- ❖ to connect members at an oblique angle

During the 19th century, the industrial revolution caused a significant transformation in wooden joinery. Steam-powered machinery and mass production methods led to a shift from labor-intensive timber frame structures with handcrafted wood joinery to balloon frame buildings with standardized components and metal connections which is the third type of the connection. Metal fastener manufacturers conducted extensive evaluations and provided comprehensive data on load-bearing capabilities. Using metal fasteners for building wooden structures, such as tables, was more straightforward than wood joinery because load-bearing capacities did not need to be calculated. Consequently, metal fasteners became more readily available and practical for constructing wooden structures. (Messler, 2011)

The use of wood joinery as a primary construction system, including these joints, declined significantly during the 19th century for timber frame and log structures. From the 1980s onwards, there was a further decline in the use of wood joinery as modular systems like platform framing and contemporary panel building emerged. These systems used metal connectors for load-bearing parts. Jeska et al. (2014) and other authors have noted that the development of modern technology, such as CNC technology and integrated workflows for design and fabrication in the mid-1980s, made it possible to design and manufacture joinery pieces with high accuracy and speed. As a result, panel, solid, and frame modern timber systems dominated the wood building industry by the early 2000s, still utilizing wood joinery and metal connections. The availability of CNC milling machines, such as five-axis and six-axis machines with robotic arms, has made it possible to mass-produce customized wood joinery at a lower cost. This technology enables the fabrication of complex geometric joints with small tolerances, resulting in cost-effective manufacturing.

This timeline figure shows the critical turning points, transitions from one timber system to another, and the evolution of linkages in timber structures. Wood joinery, which involves making connections from the material itself (in this case, wood), has several advantages. These include high de fabrication and inherent precision, efficient assembly, dimensional stability in response to temperature or moisture changes, and the ability to customize joints to meet specific tectonic needs. (Tamke and Thomsen 2009)

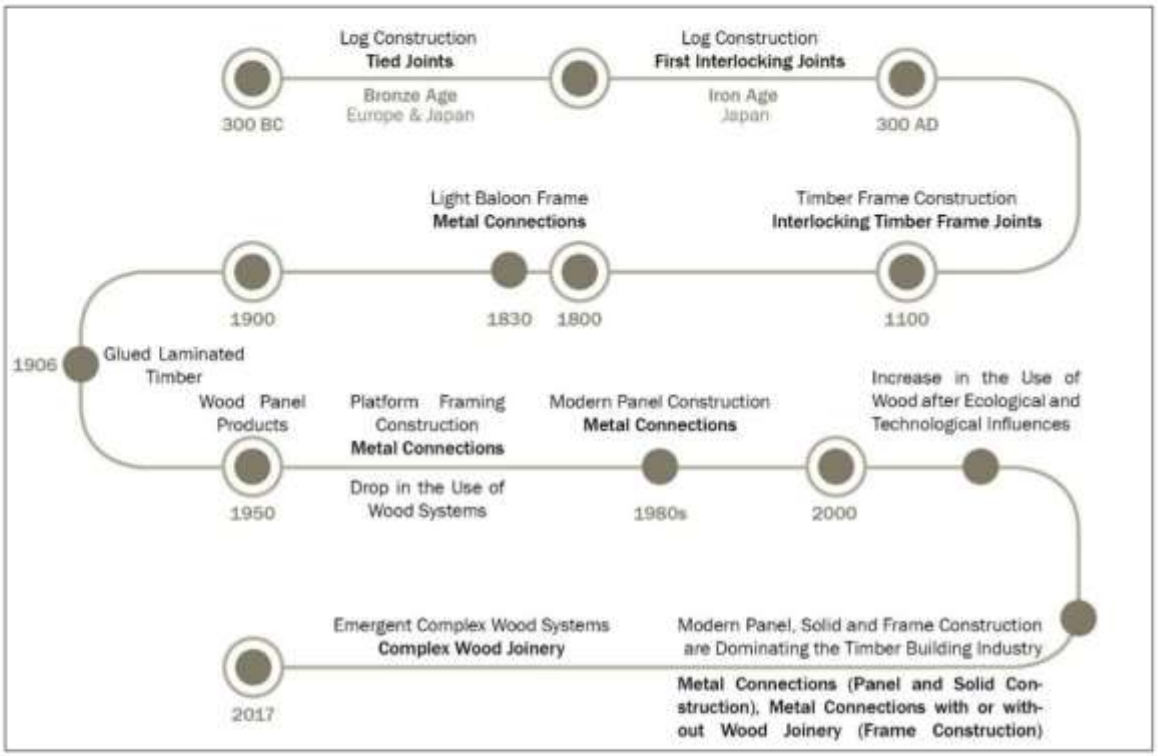


Figure 5 Timber Joinery timeline in Architecture construction

2.7 Timber Joinery

The joint is the structural aspect that allows for freedom of movement. The joint is more than just the material and its properties; it serves an essential purpose while also being a weak place. It needs care and attention. As carpenters better understood structural principles, the joinery's decorative aspect grew. The first and most important responsibility was ensuring the structure served its purpose. However, because the joint is the tiniest component in the design, it is also where we can see the evolution of decorating and aesthetic qualities. The carpenter attempted to make up for the absence of significant building problems by demonstrating more than was permitted. It was a chance to set oneself apart from colleagues and express someone uniquely. In Japan, the audience was brought closer to the performance by following the line around the column, resulting in the frequent placement of the joint at eye level. (Ernestrand 2017)

"Wood joints are also an expression of the high regard for the worked material. It is not up to humanity to pass judgment on the transistorizes of the material; at least, that is the Japanese view. Humankind has intervened in the natural lifecycle by felling the tree. Now humanity must do its utmost to handle the material as carefully as possible and do its utmost to preserve it." (Zwerger, 2015)

2.7 Type and Typology of Joinery

Timber constructions rely heavily on joints in their design and construction. In "Encyclopedia of Wood Joints," Wolfram Graubner outlines the distinct types of wood joints used in timber buildings and the techniques employed to create them. (Graubner, 1992). Corner, cross, and edge joints, Zwerger (2011) stated research on wood joinery in wood construction is noteworthy. He classifies the wooden joints into the first level, which includes the groups of Butt joint, Notched joint, Halved and Lapped joint, and Tenon joint. These common types illustrate the methods of joining two pieces of wood together.

Interlocking joints on the frame, Board, and carcass Zwerger's (2012) taxonomy applies to wood frame building joints, which are used to link linear elements. Now that more wood board materials are accessible, a broader range of joints may be used in a wood building. Gros's (1998) study, "50 Digital Wood Joints," is one of the most critical research projects on frame and board joints. The joints are described as "digital" since they were created using computer numerical control devices. The research also includes examples of how to manipulate joints, all of them for furniture. Board joints have a more extended history in furniture design than architecture, and they

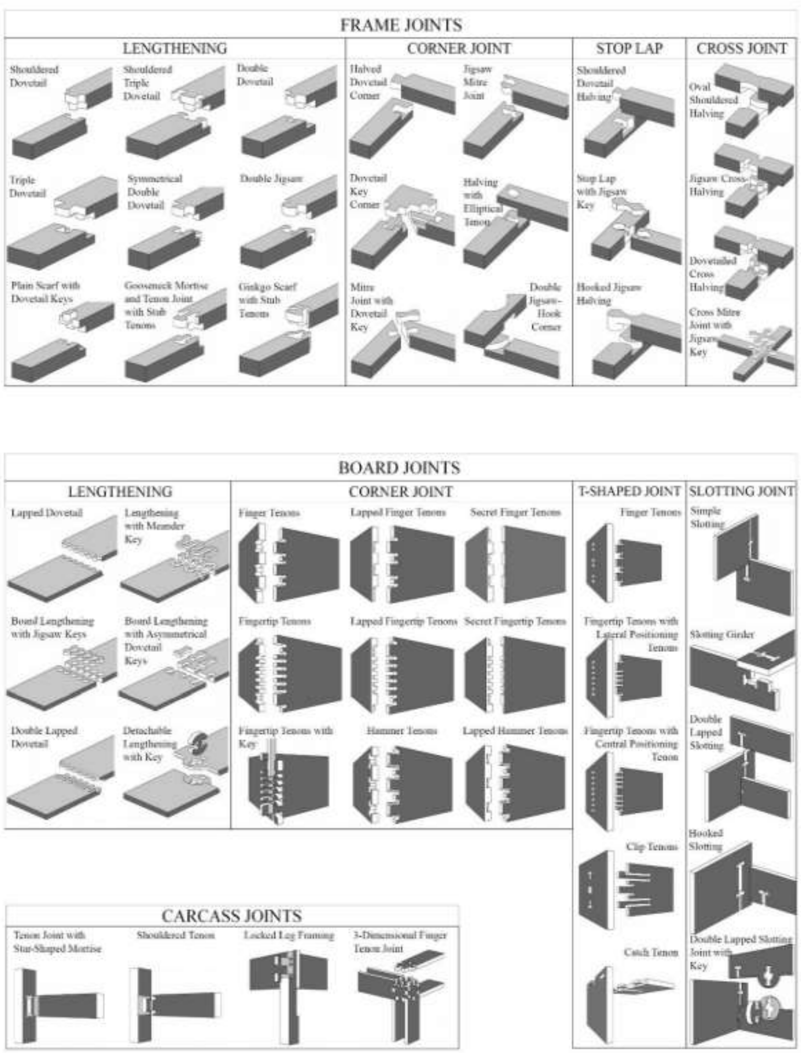


Figure 6 50 digital wood joints, adapted from Gros 1998

have only begun to emerge as structural connections or couplings for building-scale components.

This is one of the few studies that mention elastic joinery as a joint choice. The joints shown are suitable for digital fabrication and may be customized to handle complex geometry. Frame, Board, and Carcass joints are the three types of joints. Frame and board joints are divided into various subcategories: lengthening, frame corner, cross, and stop Laps joints are subcategories of frame joints, while lengthening, board corner, slotting, and T-shaped joints are subcategories of board joints. (Aparicio 2010)

2.8 Wood Joints in Complex Geometry

Integrated design and fabrication technologies were utilized to develop joints that connect wood pieces of complex surface or frame configurations in all the selected case studies where wood joinery was successfully employed as a material-driven connection type. Due to its conventional and material-driven nature, wood joinery has been used in modern structures' pavilion and roof designs with complex geometries. In terms of standard types, while some were modified, the original joint name was retained as referenced in the sources. Therefore, renaming or matching them with existing typology categorization was avoided.

- **The Clubhouse at Heasley Nine Bridges Golf Course**

Figure 8 Fabrication Process

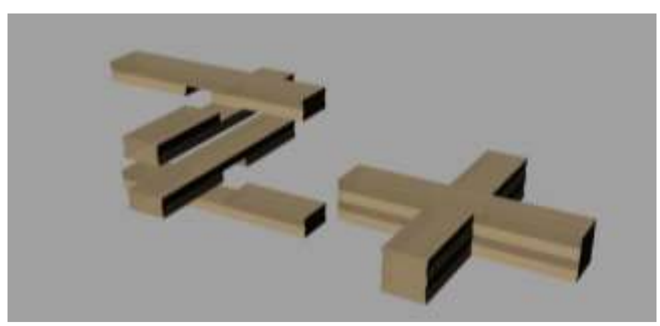


Figure 7 Halved and Scarf Joint

The club at Heasley Nine Bridges golf course is an excellent example of how wood joinery was successfully used as a material-driven connection type in a complicated structure. The wood lattice structure of the three-story building's parametric roof envelope is made of glued laminated timber beams that are joined based on 21 tree-like columns featuring both single and double curvature. The beams are connected longitudinally with scarf joints, and the intersection connections are halving joints used for the first time in an engineered wood structure. The parametric model generated fabrication plans for 3500 beam segments with 476 geometries and 15000 geometrically challenging halving joint elements, requiring a five-axis CNC machine with extra software for manufacturing customization. To enhance the durability of the standard connections, a more significant amount of screw pressure and glue were utilized in the joinery. (Jeska, Khaled Saleh Pascha, and Rainer Hascher 2015)

- **Interlocking Dovetail Joint, IBOIS Folded Plate Structure Prototypes**

The EPEL Laboratory for Timber Construction IBOIS conducted a series of investigations that involved the planning and production of various folded plate structure prototypes. One such prototype utilized dovetail joints, introduced by Robeller and Weinand in 2015 for a folding wood plate shell construction. The shells that were self-supported did not need any additional adhesive bonding. Instead, specialized algorithmic tools were utilized to create physical and virtual prototypes and automate repetitive custom details of the dovetail joints' shape while programming the joints with machine code. The integrated joints were vital in assembling the components and supporting loads, but extra adhesive bonding was still needed. However, making such bonded connections on-site is impossible because they require a curing period under specific controlled conditions like temperature and humidity.

Therefore, their application is limited to the off-site assembly of more significant components, which complicates shipping and handling and necessitates extra connections for final assembly, with few exceptions. (Source: Yves Weinand and Birkhäuser 2017)

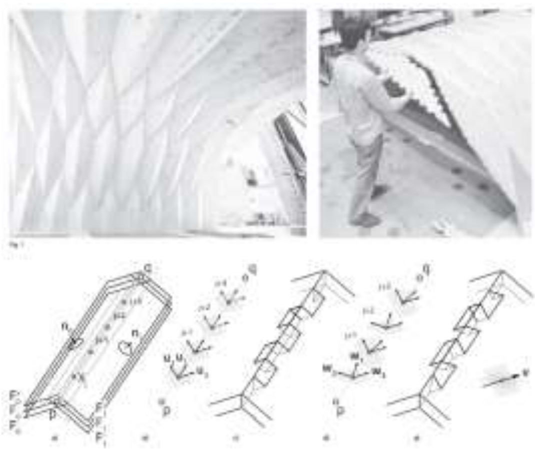


Figure 10 Interlocking Dovetail Joint, IBOIS Folded Plate Structure

Figure 9 Folded-Plate Arch Prototype Built From 12mm Birch Plywood (9-Layer). Assembled Without Adhesive Bonding Or Metal Fasteners. Span 1.65m, Self-Weight 9.8kg.

- **Interlocking Finger Joints: ICD/ITKE 2011 Research Pavilion**

The ICD/ITKE Research Pavilions utilized finger joints to attach plywood panels as part of an innovative lightweight wood folded plate system. This system was based on concepts established by the ICD (Institute for Computational Design) and ITKE (Institute of Building Structures and

Figure 11 Interlocking Finger Joints: ICD/ITKE 2011 Research Pavilion

Figure 12 Interlocking Finger Joints: ICD/ITKE 2011 Research Pavilion

Structural Design). It was featured in the ICD/ITKE 2011 Research Pavilion and Landes Garten Schau Exhibition Hall. The biomimetic characteristics of sea urchins and sand dollars were incorporated into the design to create a distinct plate structure with interlocking finger joints. At each joint, three plate edges meet, allowing the highly lightweight construction made from 6.5 mm (about 0.26 in) thin plywood sheets to transfer daily and shear stresses effectively. Advanced computational design and simulation were combined with robotic manufacturing to automate the repetitive joint details in design and fabrication. (Source: Krieg 2011, Institute for Computational Design 2011)

- **Snap-Fit Joint: Single-Folded Double-Layer Arch**

An initial investigation demonstrated the potential of using a snap-fit connection for structural dim-fit and tab-and-slot joints on double-layer structures to create a direct edgewise relationship between all four lay fold layers, providing a structural benefit. The inside panels of a fold can initially pass through each other like a mortise-and-Tenon connection, then snap onto the outside layers above using longer snap-fit connectors. This design results in two extra line joints per edge, increasing the overall stiffness and rigidity of the connection, and the inside panels double-lock the external boards in place. The snap-fit joint is employed on sloped surfaces and comprises non-orthogonal faces. The prototype was constructed using a 5-axis CNC machine. (Robeller et al.

(2014)

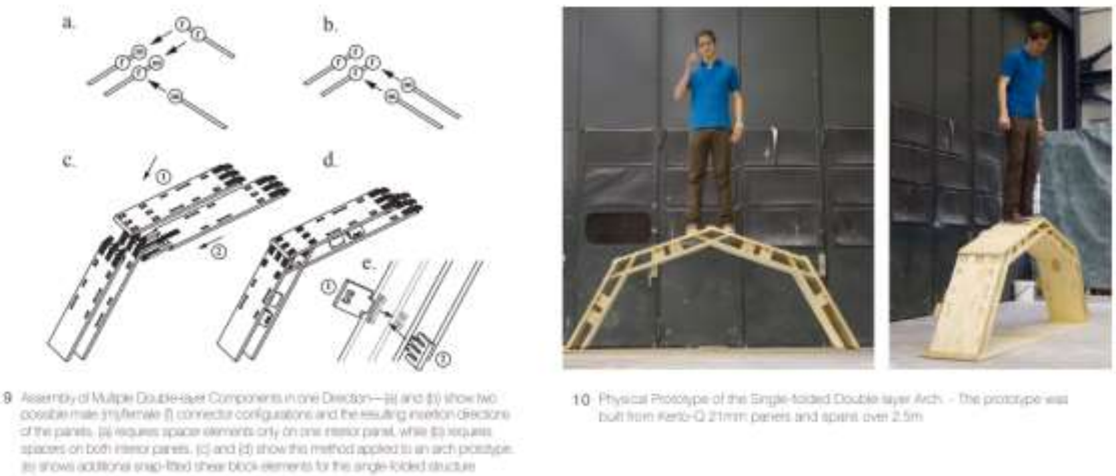


Figure 13 Snap-Fit Joint: Single-Folded Double-Layer Arch

2.9 Conclusion

The detailed study of timber joinery and modern building techniques using computational technology has become increasingly important in developing complex wooden structures. Timber joints play a critical role in supporting the load-bearing capacity of these structures, and the use of computational technology alongside advanced materials has enabled the creation of complex geometries while maintaining the design's structural integrity. This study will divide the timber structure into timber frame and plate components with rigid and elastic joints. The study will focus on developing joints for complex geometries using computer technology and structural analysis. While advanced technologies such as Multi-axis CNC machines are currently only available in research institutes and large corporations, this research aims to used simple 3-axis CNC machines and develop complex joinery techniques that can be easily replicated in the industry.

2.10 Landscape of the Thesis

2.10.1 The Wood Crafting Category

Wood crafting has been categorized as basic handcrafting for centuries. Then the 20th century, led to advanced technology Like CNC milling and mechanical arm assembly methods. "Craftsmanship names an enduring, basic human impulse, the desire to do a job well for its own sake" Richard Sennet, The Craftsman

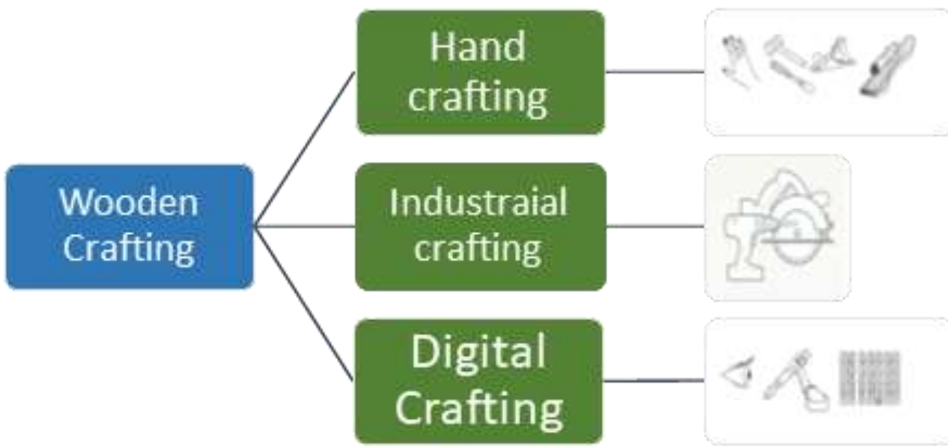


Figure 14 Wood Crafting Wood Crafting

2.10.2 The Joinery Category Is Based on the Complex Geometry

Based on the literature, wooden joinery is divided into the rigid and elastics joints

numerous methods exist to categorize and organize joints, and the amount and variety of joints created and utilized throughout history. However, for the objective of this investigation, which concentrates on the parametric modeling of joint shapes, a simplified grouping of frame and plate joints is presented in the figure

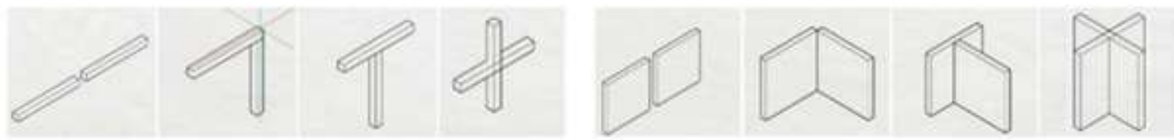


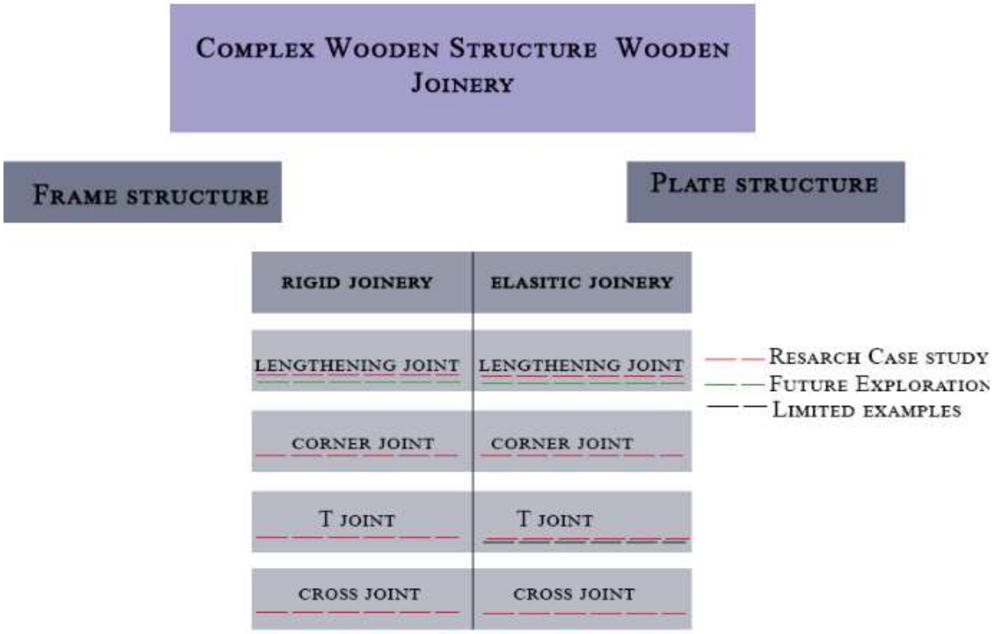
Figure 15 Frame And Panel Joints, The Lengthening Joints, Corner, T Joints, And Cross Joints.

2.10.3 Complex Structures

The basic principles of complex architectural designs encompass several notions, including freeform curves and surfaces, differential geometry, kinematic geometry, mesh processing, digital reconstruction, and shape improvement all play a role in creating intricate and innovative designs. These ideas allow architects to push the boundaries of what is possible and create structures that are both functional and visually striking. (Helmut Pottmann 2007). For the timber joinery base complex structure are both flexible and rigid joinery systems used. Elastic joints allow for movement and flexibility, while rigid joints provide stability and strength. In this study, the focus will be on the general joinery systems used in the structures. The study will concentrate on the complex wooden joinery of the corner, lengthened corner, and T-joints. These types of joints are

Figure 16 Research on Joinery

essential in providing stability and strength to the overall structure. The complex type of shell vault design uses wood the integral mechanical attachment is used for hold the individual pieces together.



By testing the rigidity and elasticity of the joinery in this structure, the researchers will better understand the strength and stability of these types of joints. The integral mechanical segmental structure is tested by incorporating various types of joineries such as Finger, Tenon Joint, and halve and scarf joint. The structure is a type of shell vault design that uses both the elastic and the rigid joinery to hold the individual pieces together. By testing the rigidity and elasticity of the joinery in the structure, the researchers will better understand the design of these types of joints base on the curvature of the shell and developed with joinery perfect for shell design.

2.11 Methodology

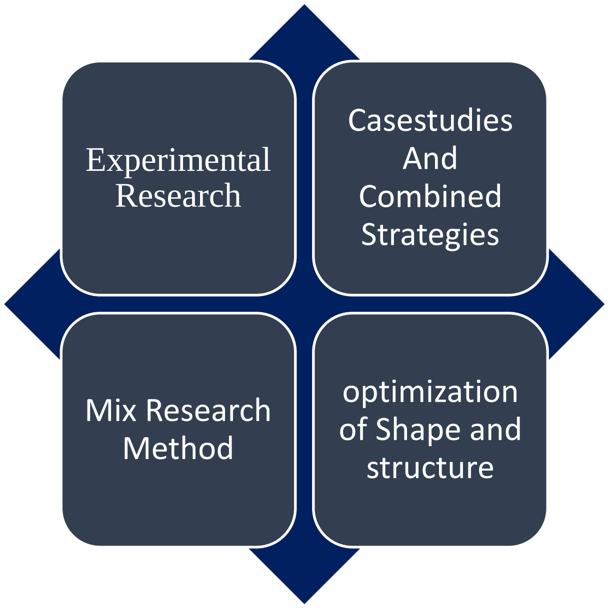


Figure 17Research-Led Design

This thesis will be written using a research-led design method that employs case studies + combination studies, and experimental research in for good measure (Figure 17). The study examines the wooden joinery in the complex structure and compares its structural stability and shape optimization by using the Finite Element Methods using the Grasshopper Plugins.

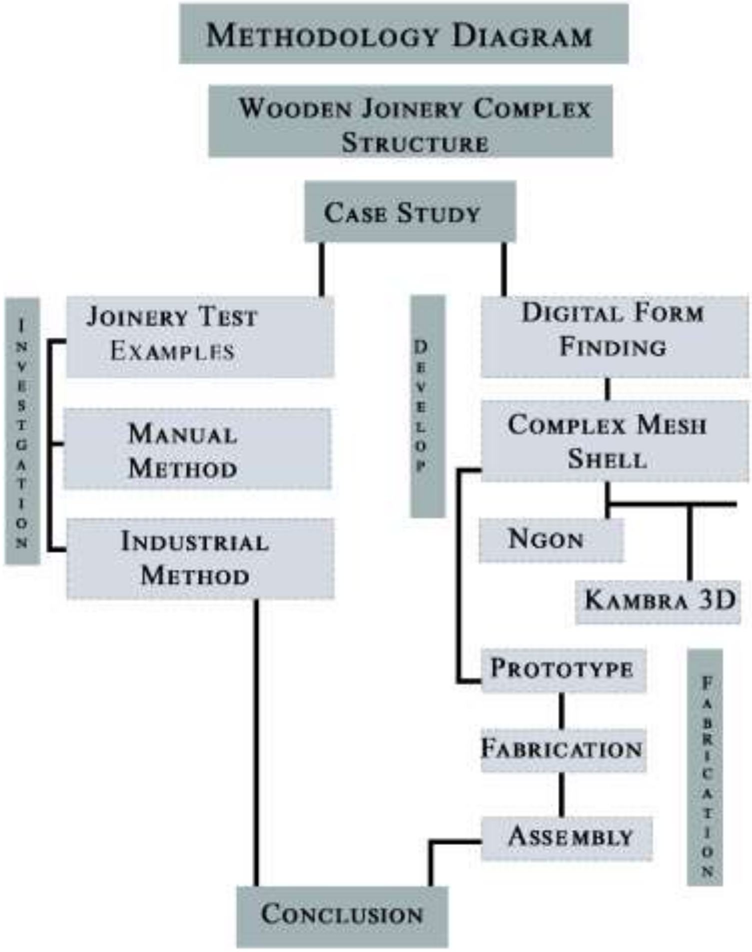


Figure 18 Shows the Thesis Plans

This is mixed-method research with a qualitative and quantitative base. An experimental study will be taken to recreate the timber joinery to understand how to adapt traditional techniques to prefabricated timber joints to make them easier to use the investigation of form, digital modeling, and jigs will then be possible. The methodology used is a case study, design modeling, and simulation (for shape and structure analysis). This study will be an empirical inquiry that investigates a contemporary phenomenon within its real-life context. The tools used for the research investigation will be digital design and modeling of the parametric complex geometry and digital optimization of structure, the fabrication technique and installation process.

2.12 Research Question

How can timber joinery systems be used to create the complex wooden geometrical structure (primarily the shell structure like vault structures) by the algorithmically computational form finding and using simple CNC 3-axis fabrication technology?

Timber joinery systems can be a powerful tool for creating complex and visually striking structures that are structurally sound and sustainable. By combining digital design and analysis tools with traditional joinery techniques, designers and engineers can push the boundaries of what is possible with timber construction.

Chapter 3

3.1 The Timber Joinery Understanding and Basic Experiment

Parametric timber joinery is a method that utilizes computer-aided design (CAD) software and computer numerical control (CNC) machines to construct precise and accurate structures. It involves creating a digital model of the joint's geometry, which is then used to generate cutting paths for the CNC machine. This technique enables efficient fabrication and quick design iterations. Various techniques for achieving mechanical attachment in timber joints include interlocking, wedge, and dowel joints. Interlocking joints involve tightly fitting interlocking shapes for a strong connection. Wedge joints utilize the natural properties of timber to create a tightening joint under load. Dowel joints involve creating holes in the wood and inserting dowels for attachment. Another approach is using separate fasteners or connectors, such as bolts, screws, or metal plates. Although this approach may not be as visually appealing as integral mechanical attachment, it offers greater design and construction flexibility, as well as the ability to disassemble and reuse the structure. (Brandon and Kaplan, 1997). One element in the planned assembly obstructs the movement of another component, thereby enabling resistance to load, facilitating connection, and enhancing structural strength. Mechanical fastening constitutes an alternative way to join objects by causing one part to interfere and interlock with another. (Messler 2006)

The Integral Mechanical Attachment process reimagines one of the world's oldest technologies. Buttons and toggles have evolved into innovative snaps, hooks, and interlocking industrial parts. Although mechanical fasteners have existed for centuries, manufacturers have recently rediscovered their benefits when used as interlocking components instead of traditional joining materials. Welding, soldering, gluing, and using nuts, bolts, rivets, and other similar devices are no longer as quick, efficient, and fail-proof as using these new fastening systems. Unfortunately, finding a single reference that provides an overview of the various fastening system categories and their applications has been almost impossible for many years. Integral mechanical attachment is one approach to parametric timber joinery. In this approach, the joint is designed to use the natural geometry and properties of the timber to achieve mechanical attachment rather than relying on separate fasteners or connectors. It can result in joints that are more robust, more efficient, and more aesthetically pleasing than traditional methods of timber joinery. (Messler 2006)

The integral mechanical attachment, also known as the necessary attachment, is a technique for connecting two or more components by utilizing a geometric feature that generates mechanical interference between the mating parts, which may also lead to interlocking. This attachment method employs specially designed or created (and sometimes naturally occurring) features incorporated into the role. In addition to its primary function in the assembly process, the capacity of the mating parts to interfere and interlock with one another to sustain position, orientation, and alignment is an inherent characteristic of the component. . (Messler 2006)

The integral mechanical attachment provides all the benefits of fasteners and some unique advantages. Fasteners and necessary mechanical attachment offer significant advantages, such as facilitating intentional disassembly, maintenance, repair, modification, or disposal. They can also join any material without changing its microstructure or composition while being simple and cost-effective compared to welding and adhesive bonding.

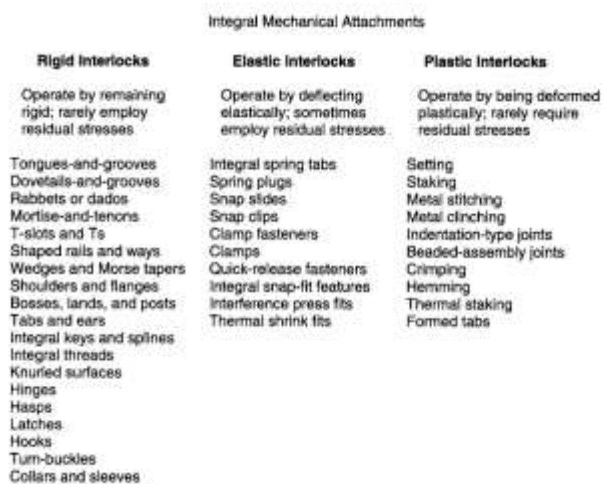
Integral Mechanical Attachment Methods and Associated Features
Using rigid Interlocks - Tongues-and-grooves - Dovetails-and-grooves , finger joinery- Rabbets or dados - Mortice-and-Tenon's - T-slots and T- Shaped rails and ways - Wedges and Morse tapers - Shoulders and flanges - Bosses, lands, and posts - Tabs and ears with recesses or slots - Integral keys and splines - Integral (coarse) threads - Knurled surfaces - Hinges, hasps, hooks, and latches - Turn-buckles - Collars and sleeve
Using elastic Interlocks - Integral spring tabs and spring plugs - Snap slides and clips - Clamps and clamp fasteners - Quick-release fasteners - Integral snap-fits (of all types) - Interference press fits - Thermal shrink fits

Figure 19 Integral Attachment Methods and Features

However, like fasteners, integral mechanical attachment can also lead to stress concentrations at discrete joining points, potential fluid intrusion or leakage if precautions are not taken, and additional weight to the assembly or structure. The ease of automation also varies depending on the technique used. Despite these shortcomings, the advantages of integral mechanical attachment outweigh any negatives, leading to its continued use throughout history, including a resurgence today.

❖ Advantages of integral mechanical attachment

Every method, process, and material has its advantages and disadvantages. None of them can be considered perfect in every circumstance, including integral mechanical attachment, according to Messler (2006a). Necessary mechanical attachment relies only on mechanical forces from interference, allowing for interlocking without bonding. It is the only method that enables intentional disassembly without



Integral Mechanical Attachments

Rigid Interlocks	Elastic Interlocks	Plastic Interlocks
Operate by remaining rigid; rarely employ residual stresses	Operate by deflecting elastically; sometimes employ residual stresses	Operate by being deformed plastically; rarely require residual stresses
Tongues-and-grooves	Integral spring tabs	Setting
Dovetails-and-grooves	Spring plugs	Staking
Rabbets or dados	Snap slides	Metal stitching
Mortise-and-tenons	Snap clips	Metal clinching
T-slots and Ts	Clamp fasteners	Indentation-type joints
Shaped rails and ways	Clamps	Beaded-assembly joints
Wedges and Morse tapers	Quick-release fasteners	Crimping
Shoulders and flanges	Integral snap-fit features	Hemming
Bosses, lands, and posts	Interference press fits	Thermal staking
Tabs and ears	Thermal shrink fits	Formed tabs
Integral keys and splines		
Integral threads		
Knurled surfaces		
Hinges		
Hasps		
Latches		
Hooks		
Turn-buckles		
Collars and sleeves		

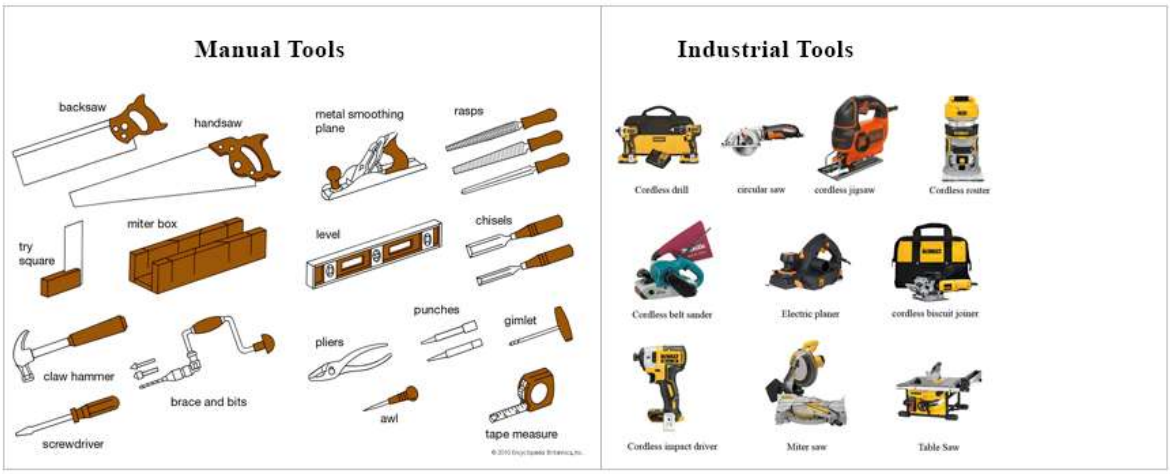
Figure 20 Integral Mechanical Attachment Interlocks

damaging the parts involved, and it uniquely facilitates maintenance, service, repair, portability, and ultimate disposal through recycling. Additionally, integral mechanical attachment is the only approach that allows an intentional motion for dynamic devices or structures, causes no changes in material microstructure or composition, and enables the joining of fundamentally unconventional materials. Furthermore, it provides a straightforward way of imparting structural damage tolerance beyond secular damage tolerance. Finally, it is inexpensive, requiring only limited operator skill compared to welding or adhesive bonding.

In conclusion, parametric timber joinery is a versatile and efficient approach to designing and fabricating timber structures. Integral mechanical attachment is one technique that can be used to create robust, efficient, and aesthetically pleasing joints, while separate fasteners or connectors offer greater flexibility in design and construction. The selection of an approach for designing a structure depends on the specific project requirements and the designer's objectives for the final product. It is worth noting that both sub-processes rely exclusively on mechanical forces to secure the parts, and integral mechanical attachment involves using geometric features inherent in the components being joined to create physical interference and interlocking.

Moreover, it is fascinating to categorize integral mechanical attachments as rigid, elastic, or plastic interlocks based on the mechanism responsible for the attachment's operation, performance, or creation. This classification can assist in comprehending the distinct techniques for designing and producing integral mechanical attachments. In addition, the logical correlation between the various interlock types and the primary material categories is crucial for co-designing virtual mechanical extensions. For example, timber structures often utilize elastic and rigid joinery techniques to create solid and efficient joints. Overall, exploring diverse types of integral mechanical attachments and their relationship with varying material classes can provide valuable insights into designing and fabricating efficient and aesthetically pleasing timber structures. For example, timber structures often utilize elastic and rigid joinery techniques to create strong and efficient joints. Overall, exploring different types of integral mechanical attachments and their relationship with varying material classes can provide valuable insights into designing and fabricating efficient and aesthetically pleasing timber structures.

3.2 Design Experiment and Modelling Iteration:



The first step is to explore the joinery system as the manual approach and then use the

Figure 21 Manual And Industrial Tools Use for Basic Fabrication

industrial method to understand the connections of timber joinery Fabrication: To investigate the manual and industrial techniques of joinery, is the reason for this study. The manual method includes the hand tools still in used today. The reason to start from that point is to understand the fabrication process of the past and realize how time-consuming the process is and took time to master the art this art for creating such a complex structure as a witnessed in Japanese and Chinese timber architecture. After the advancement of technology, the industrial evolution also affects the timber industry, especially in joinery, such as less time consumption and more accuracy in less time and large-scale construction.

3.2.1 Timber Joinery Understanding and Initial Designing

The initial experiments are done on the basics of the timber and for the basic understanding of the rigid joinery one. It will be using simple hands and tools and industrial tools. Manual joinery involves using hand tools and traditional techniques to create joints in timber, which can be time-consuming and require an elevated level of skill and practice to master. However, this method can help explore the tectonic character of wood and understand the basics of joinery. In contrast, machines such as table saws and routers can make joinery quicker and more precise, with less room for error. In addition, it is beneficial for creating complex or repeated joints, such as finger joinery, halves, and lapped joints.

Joinery	Method	Fabrication	Type	Test Joinery	Observation
Splined Grooved Joint	Industrial	Use router and table saw machine	Rigid joinery		Board system and the liner system.
Tongue And Groove Joint	Industrial	Use router and table saw machine	Rigid Joinery		Board and frame system and the liner system .
Halve And Lap Joint	Industrial	Table saw machine	Rigid Joinery		The best joinery for the board system and the complex liner and complex frame system .
Finger Joints	Industrial	Table saw machine and finger joint jig	Rigid Joinery		Joinery for the board system and the liner system.
Tenon And Mortise Joint	Industrial	Rotating method	Rigid Joinery		Best for frame structure but also work for complex segmental structure .
Dovetail Joint.	Hand tool method	Hand tools like a chisel and saw	Rigid Joinery		Best for board system .

Table 1 Observation of manual and industrial timber joinery and fabrication technique

3.3 The Parametric Joinery

It evolves into four main steps

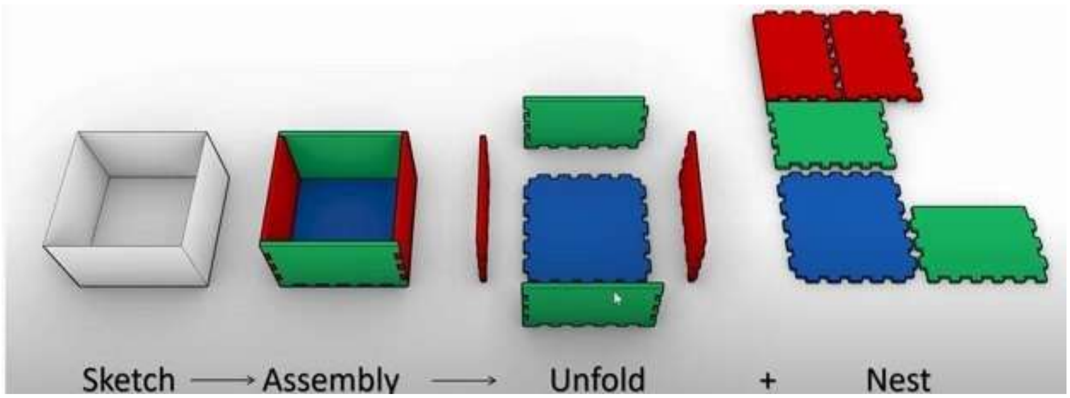


Figure 22 Maintain Steps of Parametric Joinery

- **Sketching:**

The first step, sketching, involves creating a basic concept for the joinery and the base geometry. This research focuses on the segmental timber joint, which is curve geometry.

- **Assembly:**

The second step, assembly, involves designing the joint using software such as Rhino and Grasshopper, with the latter being especially useful for joinery design. This consists of digit joint modeling, which can be modified and refined.

- **Unfolded:**

The third step unfolded involves preparing the design for fabrication by creating a flattened, 2D representation of the joint that can be used to generate the cutting paths for the CNC router.

- **Nest**

The last step, nest, involves using a CNC router to fabricate the joint from timber. This process involves using the flattened design to generate the cutting paths for the router, which cuts the joint out of the timber material. This step can be done by the cutter, a CNC router, or a 3D printer, depending on the method selected for fabrication.

Overall, the parametric timber joinery process uses digital design tools to create efficient and aesthetically pleasing joints that can be fabricated using modern fabrication techniques such as CNC routing.

3.4 Parametric Joinery Design

In this part of the chapter, the research will discuss parametric joinery and the use of Grasshopper and plugins for designing and creating complex curve geometry. *Parametric joinery* is a technique that entails crafting joints using a predetermined set of parameters, which can be modified to yield various joint variations. Rhino, a 3D modeling program, enables parametric design through Grasshopper, a visual algorithm editor. Designers can customize universal joints using Grasshopper and plugins to fit specific design requirements.

Universities and research projects often develop these plugins to explore the possibilities of parametric joinery and create new and innovative joints. In addition, using curved geometry, such as arches, vaults, and domes, allows for complex designs that can be explored in further research. Overall, parametric joinery and Grasshopper can enable designers to create more efficient, adaptable, and customized joints to fit specific design requirements.

3.4.1 Parametric Rigid Curve Base "Halved and Lapped" Joint

The aim is to develop a Grasshopper definition for lengthening frame curve joints for the liner wood member of various geometries, including the straight, arch, and non-uniform rational (NURBS) curves of the second and third curves. The importance of these lengthening joints lies in their ability to fabricate complex timber structures from smaller or segmental members.

The fabrication of complex timber structures often involves the tessellation of nonstandard and non-Euclidean geometry into fabricable geometry. In previous research, frame, and plate members have been used. However, for complex timber geometries, the segmental process is the easiest way to create a fabrication system that can be milled or cut using different techniques, such as laser cutting or CNC machines, with minimal waste.

The Grasshopper definition being developed will allow for the lengthening of frame curve joints for liner wood members of different geometries, thus enabling the fabrication of complex timber structures with minimal waste. In addition, this will make it easier to create unique and nonstandard designs that would have been difficult or impossible to achieve using traditional fabrication methods.

For the timber joinery frame construction, the lengthened joints used for the columns and beams increased required amount than natural wood obtained from natural resources; Zwerger (2012) describes the prolonged joint study as the end grain to end grain sliced joints such as halved and lapped and Tenon and mortise joint.

There are many ways to create parametric joints. Some courses are manual, and some are Grasshopper. The case studies will explore all the possible ways to make curve arch joinery. A few Methods are selected to create the 3-for the research dimensional parametric joints. The joints are decided based on the number of control points that make out the joint geometry for parameterization. Using the Grasshopper script for the basic design iteration, it is possible to generate the different joints for the 2d and 3d another degree NURBS curve Fig 22 by changing the number and the location of the control point, making it possible to create different options by changing few parameters.

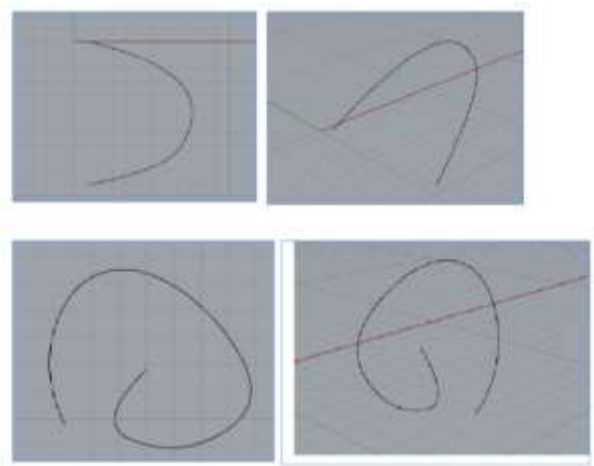


Figure 23 2d And 3d NURBS Curves

3.4.1.1. The Design Iterations and Their Grasshopper Scripts:

The Grasshopper script is designed to create halved and lapped joints and Tenon and mortise joints for curved arch geometries. The research is based on the curvature of geometric timber joinery, and the parameter modeling procedure with the Grasshopper is done in diverse ways to achieve a collaborative group.

The Grasshopper script involves creating the geometry profile, a curve geometry such as an arch, and the joinery profile. Then, the joinery profile is targeted to the curve curvature of the geometry profile using the suitable Grasshopper profile. The difference between the standard types, such as halved and lapped joint and Tenon and moist joint, is likely how the control points are ordered, and different scripts are used to explore these differences.

The figure shows examples of the Tenon and moist joints created with the Grasshopper script.

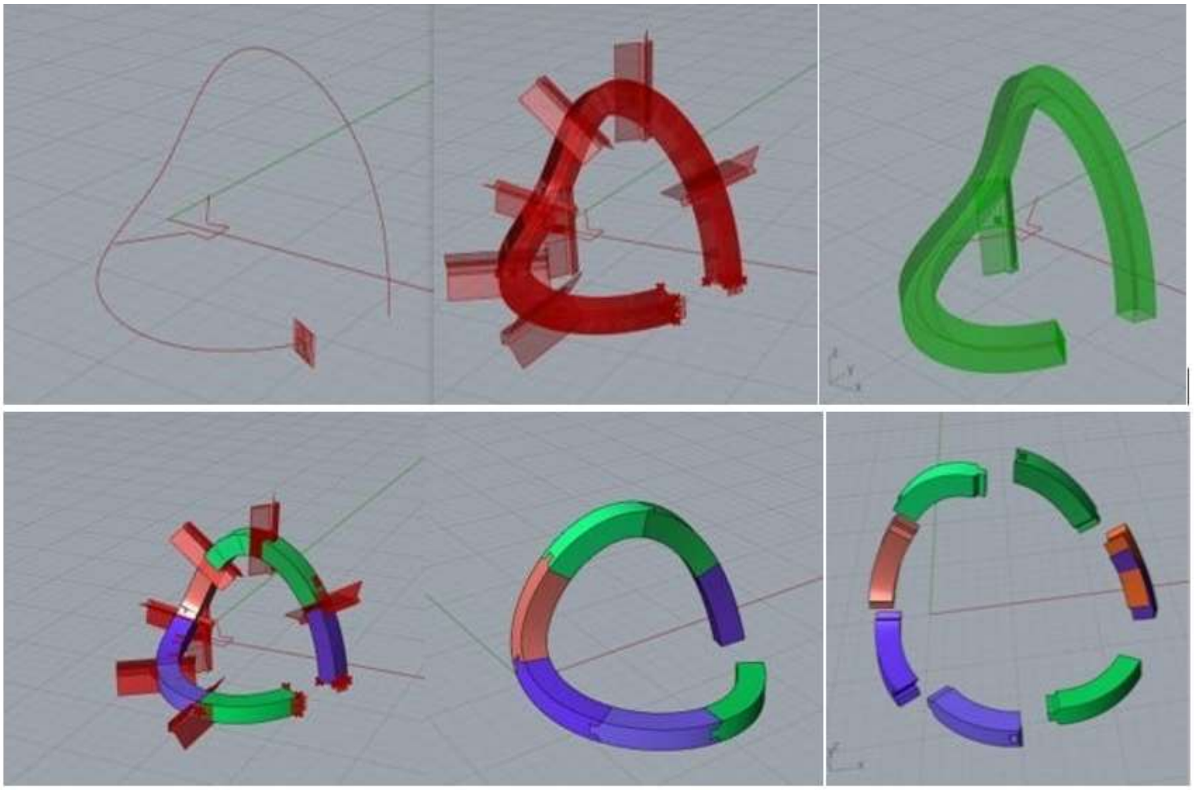


Figure 24 Tenon And Mortise Joint Parametric Joint Process

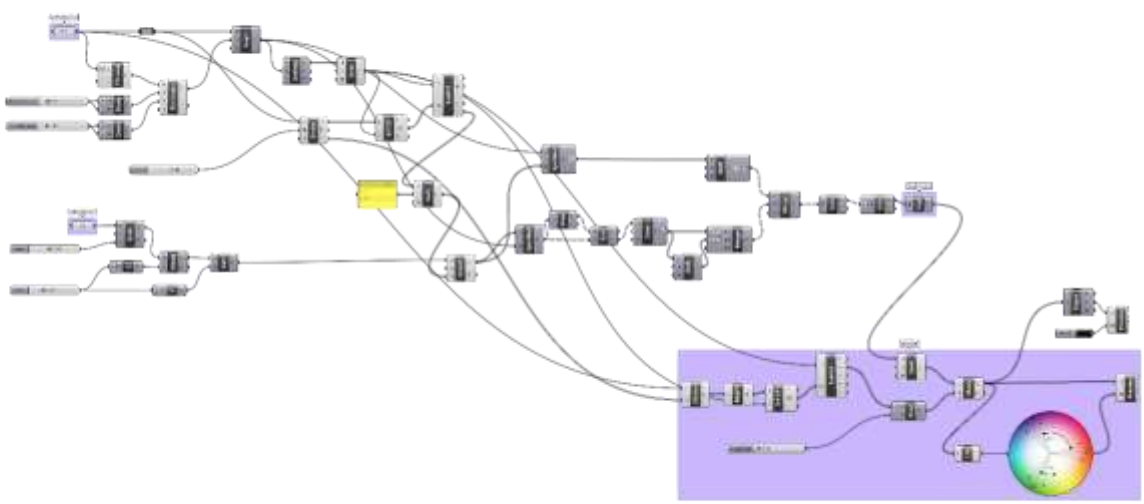


Figure 25 Grasshopper Definition of Tenon and Mortise Joint

This type of connection involves inserting a Tenon, a protrusion located at the end of one piece of wood, into a mortise, a cavity in another part of the wood, to establish a reliable connection. Creating a Tenon and mortise joint, specifically using curve geometry profiles to generate the joint's shape .The precise fit between the shapes of the Tenon and mortise is critical to producing this joint. Careful design is necessary to achieve this accurate fit. One way to do this is to use a curve geometry profile input, which defines the center line of the frame members and generates the joint profile. This profile determines the shape of the joint and the position of the joint's control points, which are critical for ensuring a secure and stable connection.

Using a script to create the joints can help ensure consistency and accuracy. However, it is essential to take care in designing the joint profile and selecting appropriate materials and dimensions to ensure that the joint will be strong and durable.

The process is based on the following main steps.

- ❖ Firstly the geometry and the joint profile is selected to generate the frame 3d as a boundary.
- ❖ Then, the S surface, the 3D object, is split into the standard geometry as described
- ❖ The surface is partitioned into several sub-surfaces that are regulated and segmented accordingly. Finally, the design of the joints is projected and controlled, and subsequently, points are projected onto each of the sub-surfaces.
- ❖ A loft surface of the profile is created the joint output is formed.
- ❖ Then for the fabrication, the Grasshopper script is baked. Finally, the joinery is the segmental base frame structure.

Using digital tools for designing and prototyping joints, specifically the halved and lapped joint is an essential process in woodworking. Like the Tenon and mortise joint, this type connects two pieces of wood. The halved and lapped joint involves halving and lapping the ends of two pieces of wood to create a strong connection. To develop such joints using digital tools, it is crucial to consider the constraints and requirements of the joint design. For instance, when dealing with a joint with double curvature, it is necessary to mill the edge with rounded corners and the flexibility to adjust the radius based on the milling tool head's diameter. By utilizing digital tools like computer-aided design (CAD) software or 3D modeling tools, designers can produce and test various joint designs and make necessary adjustments to the joint's profile and dimensions before production. This can help ensure the joint is functional and aesthetically pleasing while minimizing the risk of errors or flaws in the final product.

3.4.1.2 Halved and Lapped Joint

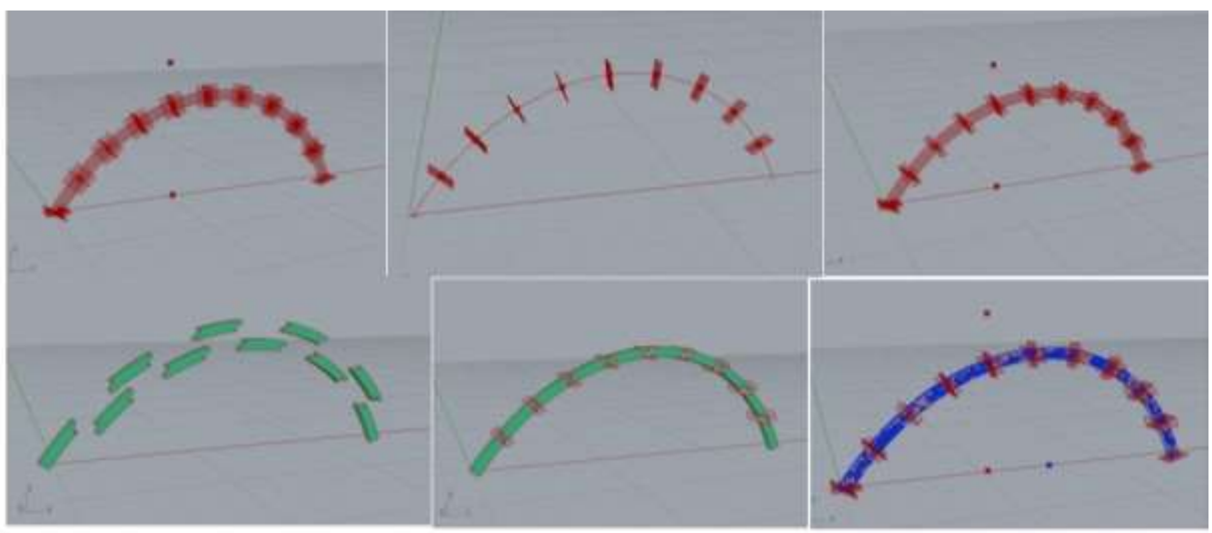


Figure 26 Halved and Lapped Joint

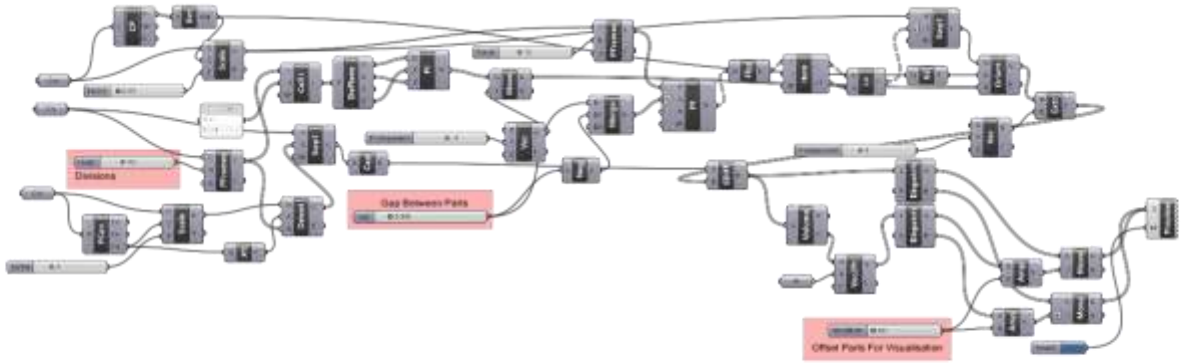


Figure 27 Halve and Lap Joint Grasshopper Script

The script is an exceptional design for the parametric halved and lapped joinery for the frame structure.

3.5 Currently Used Computational Design Tools for Timber Joints

3D modeling tools and CAD/CAM software have played a significant role in the resurgence of timber joints in contemporary architecture. These tools allow architects and designers to create and test complex joint designs and generate geometry and fabrication files that can be used for CNC machining and other forms of automated fabrication. Various CAD/CAM software packages like Cad works, Sema, and Ligno cam provide specialized joinery modules for timber frame constructions, which can export toolpath for machining from 3D models. Also, web applications like Maker Case, Cut CAD, Kyub, and Joinery, which are open source, allow the creation of joints between planar pieces that can be cut and assembled in 3D, making the process convenient. Researchers have also developed innovative approaches to collaborative design using 3D modeling tools. Larsson and colleagues created an interactive tool called Tsugite. Utilizes a voxel-based approach to exploring, designing, and producing action of intricate joints between timber beams. By restricting the design space to a 9x9x9 voxel grid, the user can analyze the joint's performance using multiple criteria after each iteration and adjust the design accordingly to improve it.

To simplify designing and producing timber joints, custom plug-ins have also been developed for Grasshopper, a visual scripting interface for Rhinoceros developed by McNeel and Associates. These plug-ins enable designers to create intricate joint geometries and generate fabrication files directly from the Grasshopper interface.

3.5.1 A Few of These Plug-Ins are explained in the Details Following

- **The Briber plug-in**

The Biber-Plugin is a Rhino-Grasshopper plug-in that provides a toolset for parametric joinery. It was created in collaboration with Germany's Hochschule Mainz Robolab to enable the joinery industry to take advantage of parametric design workflow in Rhino+Grasshopper, making out-of-the-box design and production more accessible and more affordable.

Some of the key features provided by the plug-in include an easy-to-understand and implement workflow for building complex joinery assemblies, an extensive library of join types (including both classic and advanced types), the ability to clean up corners and remove collisions, and the ability to use actual materials and incorporate dissimilar materials and joins in the same assembly. The plug-in also provides options for easy unfolding, nesting, designing and b, and building sub-structures and scaffolding to guide and support installation.

However, it is essential to note that the Biber Plug-in has some limitations. For example, it only works for linear framed lengthened joinery and only for surface curve geometrizing these plug-in sites. Therefore, working with mesh geometries or more complex segmental plugging may be challenging. Nevertheless, it is crucial to carefully evaluate its limitations before making a decision regarding its suitability for implementation in parametric design workflows, such as those found in food4rhino . However, it is important to consider its limitations carefully before deciding whether to use it in a particular project. (Teltenkötter n.d.)

Working with mesh geometry becomes challenging when dealing with a large number of segmented complex geometries. The Biber has several limitations. It only works in the linear framed lengthened joinery with only for the surface curve geometry.

Figure 29 Surfaces Lengthen Geometry

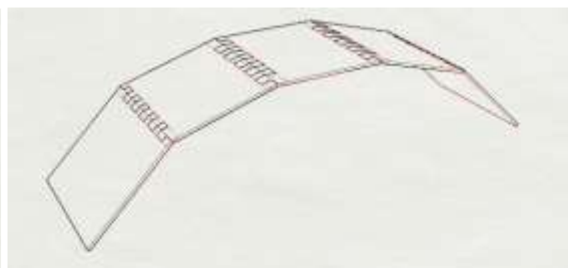


Figure 28 . Apply Joinery

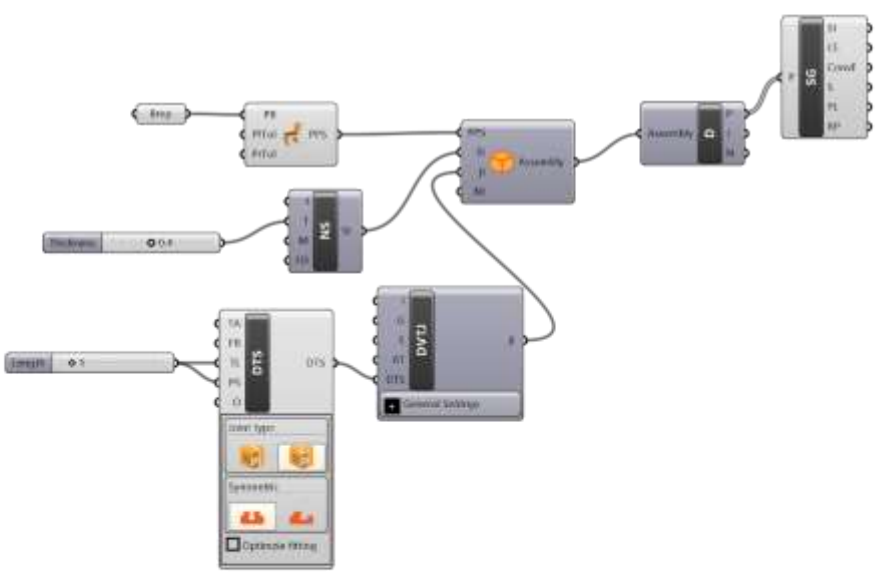


Figure 30 Simple Finger Joinery Script Using the Biber Plugin

- ❖ **The Timber Plate Structures TPS Plugin**

The "TPS_Diamond Mesh" feature on Grasshopper enables designers to efficiently create diamond folate, also known as Yoshimura folds, using freeform surfaces. This feature is specifically designed for constructing discrete plate structures, such as timber constructions, which consist of separate pieces connected by joints.

To use the "TPS_Diamond Mesh" component, designers must connect their Rhino surface to the "Input Surface S" parameter. If they want to use Grasshopper Breps, they must first deconstruct them into individual characters. Designers can then set the division in the U and V direction using the "Input division U and V" parameters. If they need to swap U and V, they can use the _direct command in Rhino and select "swap UV."

The "TPS_Diamond Mesh" component can be valuable for generating diamond folds based on freeform surfaces. However, designers should remember that it is meant for discrete plate structures and that the resulting meshes may not be flat-foldable like in Origami. (food4rhino) Work for the Finger and milled joint. Shell segmental mesh parts are suitable for this plugin, and the large shell curve structure works suitably with the mesh one. It is developed perfectly for the curve origami shell structure.

This has a limitation as well work on open mesh with transparent edges and large scale only to Crete the Joinery compatible with the Finger, dovetail, and mitered joinery.

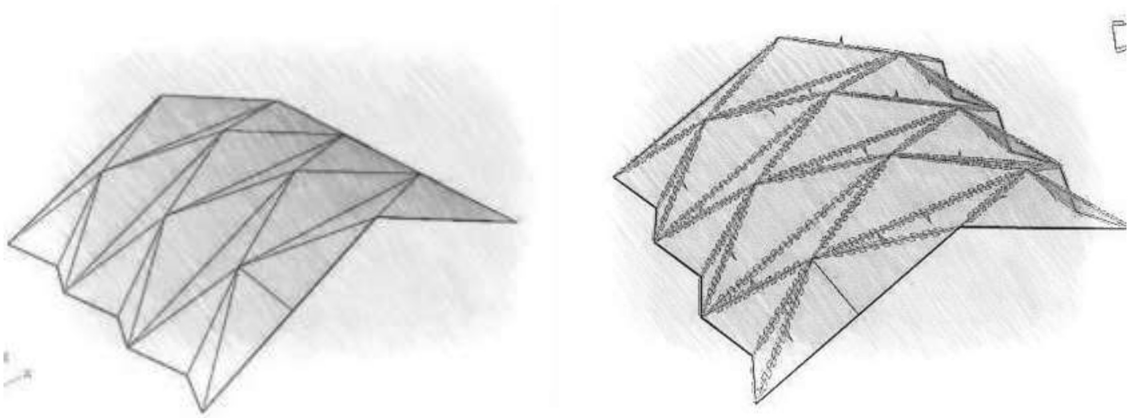


Figure 31 the Mesh Defines the Edges of the Dovetail Joinery

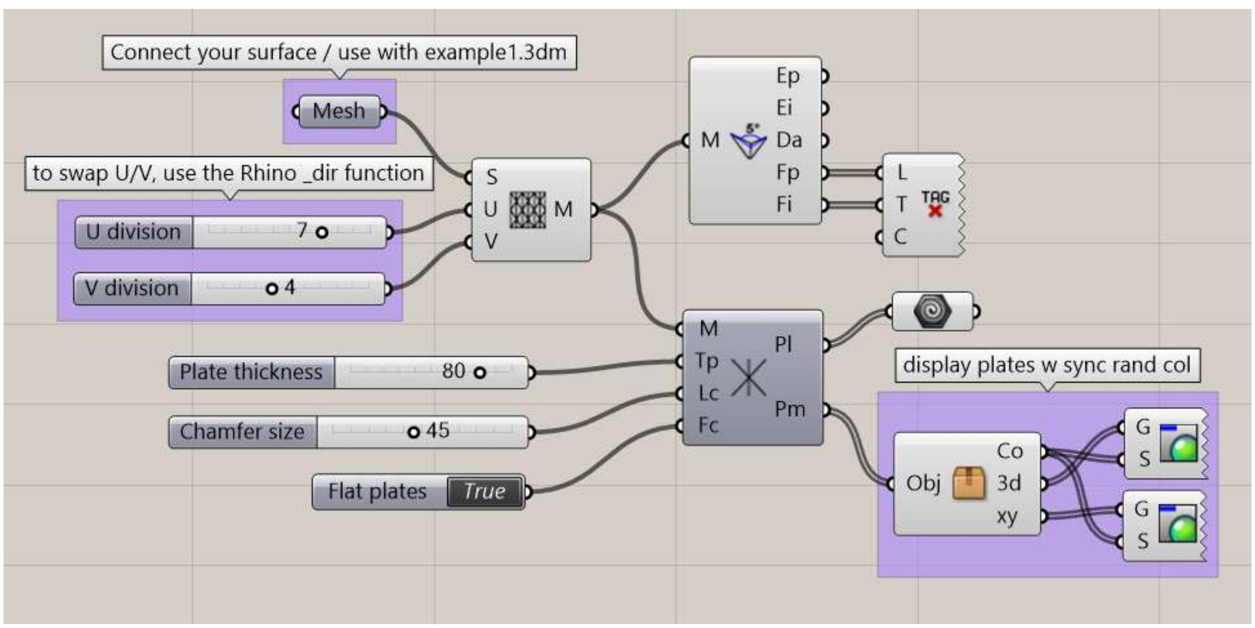


Figure 32 Timber Plate Structure Grasshopper Script

- **NGon**

The NGon Create query allows users to create N-sided polygons. At the same time, the Vertex, Edge, and Face Adjacency Utilities provide tools for manipulating and analyzing the connectivity between vertices, edges, and faces within the mesh. In addition, the Subdivide query enables users to subdivide the mesh into smaller polygons, while the Planarize query helps ensure the mesh is planar and flat. Finally, the Transform query allows users to transform the mesh in several ways, such as scaling, rotating, and translating. The Timber Joinery Methods query provides tools for creating timber joinery connections within the mesh, allowing users to simulate the structural behavior of timber elements within the mesh.

Overall, the Mesh NGon Methods and Timber Joinery Methods plug-in provides a robust set of tools for creating and manipulating complex polygonal meshes within Grasshopper and Rhino, which is particularly useful for designers and architects working with complex curvilinear surfaces. (Para house .com)

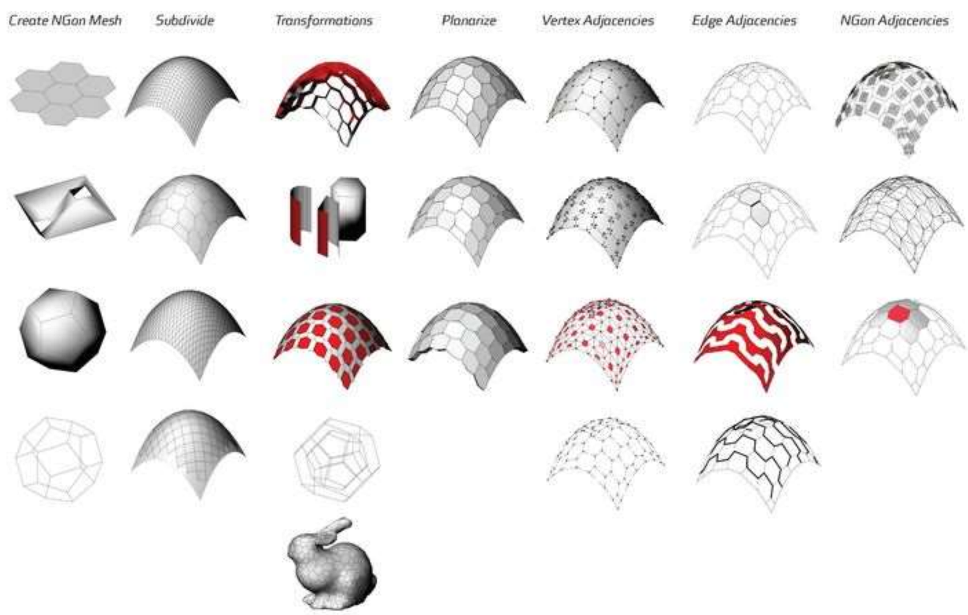


Figure 33 NGon Surface to Joinery

Empf The joinery is projected on the mesh design on the Grasshopper, and the control point is used to distance the joints and fabrication process. It used the five-axis, CNC Mill .These plugins are commonly used for joinery. However, there are other plugins available that cater to specific needs. For instance, The Reindeer is an open-source toolset that focuses on timber frame connections and supplies feedback on structural analysis. GluLamb is another plugin specially designed for creating curved glued laminated timber pieces, which can be daunting when using traditional joinery methods. Emarf offers various tools to develop timber joints between extruded solids and export fabrication files to ensure the feasibility of the joints. It is worth noting that assembly constraints can influence the joint shape, and determining the feasibility of the assembly is usually left to the user. As the number of joints increases, assembly constraints can become more complex, making it challenging to solve them. The Tsugite solver evaluates friction areas to determine the ease of inserting each proposed joint. At the same time, the TPS plugin computes a compatible vector of insertion for each piece in the structure before generating the joints. Overall, it is essential for designers and architects to carefully consider their joinery needs and choose a plugin or tool that is best suited for their specific project requirements. (Rogeau, Latteur, and Weinand 2021)

3.6 Conclusion:

In this chapter, the digital prototype design is done illustrated in the preceding section.. One example of such experimentation is using the timber shell segmental integral mechanical attachment technique, which involves using clip and Tenon mortise joints to prepare for fabrication. The NGon Plugin is a valuable tool for joint timber design, as it allows designers to create standard complex geometries and generate fabrication files directly from the plugin interface. The plugin is practical and adaptable for creating joinery in linear and curvilinear geometries, making it a versatile tool for joint timber design. When designing integral features, it is essential to consider the complexity and loading requirements of the joint, as additional assistance or enhancement may be required to ensure the joint is sufficiently rigid and able to resist loading. The timber shell segmental integral mechanical attachment technique, which involves using clip and Tenon mortise joints to prepare for fabrication, is an example of such experimentation. This technique is based on segmental shell plates and constant geometry. While this technique can be effective, it is essential to carefully consider the design of the joint to ensure that it can withstand the required loads and provide the necessary rigidity.

In some cases, additional reinforcement or enhancement may be necessary to achieve these goals. In general, digital prototyping and experimentation are crucial stages in the design process that permit designers to refine and assess their concepts before advancing to production. The NGon Plugin is a valuable tool for creating timber joints since it allows for intricate geometries and the generation of fabrication files from the plugin interface.

Chapter 4

4.1 Digital Designing Curvilinear Curvature for Timber Structure

Designing a curvilinear curvature for a timber structure can be achieved through various methods. Here are steps taken as followed:

- **Determine the Geometry of the Desired Curvature:** This involves deciding on the curvature's radius, height, and width. The desired curvature can be sketched or modeled using a software program.
- **Choose the Timber Species**: The timber species chosen will depend on the curvature's radius and the required strength. Species with high modulus of elasticity and strength properties are preferred.
- **Create A 3D Curvature Model: Generate** a 3D model of the curvature by employing computer-aided design (CAD) software. The model should include all the necessary details, such as the curvature's geometry, dimensions, and material properties.
- **Determine the Structural Loadings**: The curvature's structural loadings should be determined to ensure the timber structure can support them. Loadings include gravity loads, wind loads, and seismic loads.
- **Analyze the Curvature:** Using structural analysis software, analyze the curvature to determine its structural behavior. This includes checking for strength, stiffness, and deflection.
- **Detail the Curvature:** Detail the curvature by specifying the required connections, joints, and fasteners. Ensure that the detailing is adequate to withstand the loadings and provide durability.

- **Fabricate The Curvature:** The curvature can be fabricated using various methods, such as laminating, steam bending, or CNC routing. Ensure that the fabrication process follows the design and detailing specifications.
- **Install The Curvature:** The curvature should be installed according to the design and installation specifications. Ensure the installation is performed by qualified personnel and meets all safety requirements.

In summary, designing a curvilinear curvature for a timber structure requires careful consideration of the geometry, material properties, loadings, analysis, detailing, fabrication, and installation. A comprehensive approach considering all these factors will result in a safe and durable structure that meets the desired aesthetic and functional requirements.

4.2 Parametric Joinery Design Prototype: `

After conducting studies on digital prototypes, the wood joinery was categorized into two types: elastic and rigid. Out of the 50 digital joints enumerated by Gros in 1998, one was the flexible joint. Gros identified a detachable joint called the Clip-Tenon joint, which uses the suppleness of multiplex plywood, as an example of an elastic joint. This joint has already found application in various other industries and can be quickly produced. When exploring joinery for intricate wooden structures, the only way to consider this joint is by thinking about engineered wood products, which have made it possible (based on thesis one). The following research will focus on the basic rigid and elastic joinery, comparing which suits the complex shell structure. These joinery systems have advantages and disadvantages, both flexible and rigid, but for now, let us call it the joinery parametric joinery, not specific in general. In a bulky frame with a segmental or plate base, joint damage will only affect the segment and not the entire structure. The assembly and disassembly of the structure are effortless, and it can be done repeatedly without any difficulty. In addition, large-scale timber fabrication can be easily accomplished using simple techniques such as laser cutting machines and CNC milling.

Using the parametric joinery, any folded segmental surface can be transformed by adjusting the differential angles between the segments. The joint application is not dependent on the material of the segment being used but rather on the characteristics and properties of the material itself.

4.3 Preliminaries of Shell Theory and Shell Designs:

Architects and structural engineers have long been fascinated by the elegant and efficient forms of shells, which are one of the oldest and most effective structural designs. Shells possess inherent stability and can withstand external loads without additional support systems. The curved shape of shells not only provides aesthetic appeal but also enhances their structural performance. By curving in multiple dimensions, shells can evenly distribute loads across their surfaces, effectively balancing tensile and compressive stresses. This results in stable structures capable of spanning large distances without additional support. Furthermore, shells offer a high strength-to-weight ratio as they can carry external loads through internal forces, allowing for lightweight construction without compromising strength. This makes shells an attractive choice for architects and designers looking to create spacious environments with minimal visual obstructions. Concrete, steel, and timber are commonly used materials for shell construction, each with its own advantages and disadvantages. The material selection depends on factors such as structural requirements, environmental considerations, and aesthetic preferences. Throughout history, shells have captivated architects and structural engineers with their versatility and efficiency in construction. (Engel, 1997) (Farshad, 2013). Shell theory is a branch of structural mechanics that deals with the behavior of thin, curved surfaces under external loads. Stresses and strains in shells and their deformation and stability can be calculated using this method. Shell theory is essential for designing shell structures, providing a theoretical basis for understanding their behavior.

Geometry form finding is another essential aspect of shell design. It involves finding the optimal shape for a shell structure based on its intended use and structural requirements. Various techniques can be used to accomplish this, including physical models, computational simulations, and mathematical optimization. Structural typology refers to classifying shell structures based on their form and construction. This includes identifying several types of shells, such as dome, barrel, and shell vaults, and analyzing their structural behavior and performance. Building methods for shell structures depend on the materials used. Timber shells, both conventional carpentry techniques and modern techniques such as LVL (Laminated Veneer Lumber) and CLT (Cross Laminated Timber) can be used. Additionally, in recent years, digital fabrication methods, which involve CAD, CAM (Computer Aided Manufacturing), and robotics for manufacturing intricate curved shapes with accuracy and speed, have become more prevalent in producing shell structures. (Xiang 2017)

To summarize, many searches and concepts related to shell structures cover various fields, such as structural mechanics, geometry form finding, structural typology, and building methods involving unconventional materials. Furthermore, utility fabrication techniques are gaining more importance in creating and constructing shell structures.

4.3.1 The Computational Geometry Approach:

Segmented timber shells allow for the efficient and cost-effective construction of long-span, double-curved shell structures. (Sonntag et al. 2019) In addition, they used a zero-length spring system with dynamic nodal masses for form-finding to determine a funicular compression-only shell, a highly efficient form for carrying loads. This method involves using virtual springs and assemblies to simulate the behavior of the shell structure under external loads, allowing for the optimization of the form for maximum structural efficiency.

Surface discretization into planar polygons with a hexagonal-like honeycomb structure and later division into triangular nodes was used to realize the single curved form with flat timber segments. This allowed for the efficient and cost-effective fabrication of the shell structure using well-known timber fabrication methods.

Combining these techniques resulted in a structurally efficient compressive shell with a complex form, which could be demountable for easy disassembly and reassembly. This approach demonstrates how integrating distinctive design and fabrication techniques can result in innovative and efficient structural solutions. (Harding and Lewis 2013)

4.3.2 Computational Form Finding

"Form-finding" refers to the conventional meaning of shell structure design. This involves utilizing natural systems as a basis for processes and employing fundamental principles of structural theory and growth as techniques to establish the essential guidelines for determining the shape of the shell structure.

Computational form finding is an essential aspect of the design of shell structures. The process utilizes computational methods and tools to identify the best design for a shell structure, considering its intended purpose and structural needs. A typical method for computing the shape of a structure is to utilize finite element analysis (FEA) software, which enables the prediction of the response of the shell structure to external forces. This involves discretizing the shell surface into small elements, which are then analyzed using FEA to determine their deformation and stresses. The results of the FEA simulation can then be used to adjust the shape of the shell to optimize its structural efficiency. Another approach to computational form finding is using optimization algorithms to find the optimal condition of the shell structure. This involves defining a set of design parameters, such as the shell's shape and its elements' thickness, and then using optimization algorithms to find the combination of parameters that results in the best structural performance. Machine learning techniques have recently been applied to computational form-finding for shell structures. This involves training machine learning models on a dataset of shell structures and their associated performance metrics, such as stress and deformation. Once the model is trained, it is possible to produce fresh designs tailored to meet performance standards.

Overall, computational form finding is an essential tool for the design of efficient and effective shell structures. It allows for optimizing the shape and structural performance while providing insight into its behavior under external loads. There are two main methods for determining the form of shell structures: physical and digital. Historically, physical techniques have been used for shell design, as seen in the work of shell experts such as Antonio Gaudi, and involve simulating the form through physical means. Observing structures in nature has revealed that many structures are energy efficient, leading to the development of biological methods. Digital techniques were later developed based on physical processes and utilized mathematical concepts for computer simulations. Recent studies have elaborated on digital form-finding techniques. The principle of reversing physical hanging nets, which can only support tension, to operate in pure compression was discovered by Robert Hooke in the 17th century. This principle results in compressive forms with zero bending under self-weight, allowing for a thin structural depth with no out-of-plane forces. (Harding and Lewis 2013)

4.3.4 A Digital Design Process for Shell Structure

The process involves creating a system of connections using form-finding and planarization methods. Due to the hexagonal discretization used at the beginning of the process, the dimensions are not whole numbers.

The digital design process for shell structure includes the following steps:

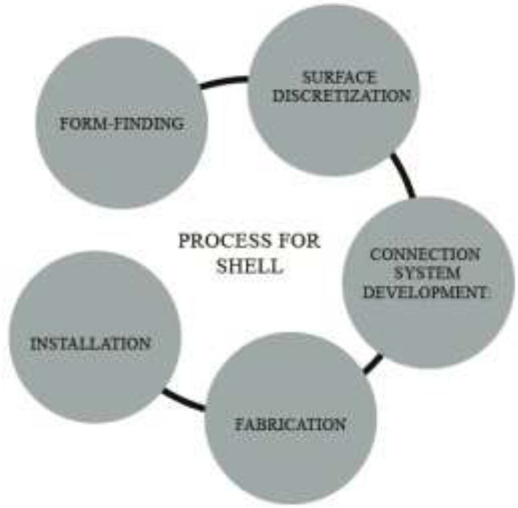


Figure 34 A Digital Design Process for Shell Structure

- ❖ **Form-Finding:** A method called form-finding, which may involve using a zero-length spring system with dynamic nodal masses, is utilized to determine the shape of the shell structure. This technique results in the creation of a compressive shell that is both structurally efficient and has a sophisticated design.
- ❖ **Surface Discretization**: The shell surface is divided into planar polygons with hexagonal-like honeycomb structures and later into triangular nodes. This allows for the realization of the single curved form with flat timber segments cheaply and efficiently.
- ❖ **Connection System Development:** A connection system considers the hexagonal discretization, other geometrical parameters, and structural and fabrication restrictions. Grasshopper® functions and plugins implement the process through parametric modeling, providing greater control over the results for each stage.
- ❖ **Fabrication:** The final design is fabricated using simple methods like laser cutting and CNC milling, allowing for efficient timber segments and connection system production.

- ❖ **Installation:** The wooden parts and their attachment method are assembled where they will be used. This creates a structure that can be taken apart and back together again quickly, making it convenient for transportation or use in the future.

In general, this digital design process allows for the creation of intricate, efficient, and cost-effective designs for shell structures with high accuracy and control. The geometrical parameters include three-point supports and openings, considering all manufacturing constraints and geometric properties. These approaches are detailed in the subsequent sections. The process is carried out using Grasshopper® functions and plugins through parametric modeling. Due to its interoperability, the entire design process can be managed in a single workspace, providing more control over the outcomes at each stage. First, a connecting system must be developed through form-finding and planarization procedures. The dimensions are not part of the approach integers since they consider the hexagonal discretization applied at the outset of the process. The geometrical parameters consist of three-point supports and three apertures, which consider geometric properties and structural and manufacturing constraints, which are discussed further in the subsequent sections. By using Grasshopper® functions and plugins for parametric modeling, the entire design process can be managed in a single working environment, resulting in greater control over the outputs at each stage.

4.3.4 Form-Finding-Hexagonal Subdivision and Planarization

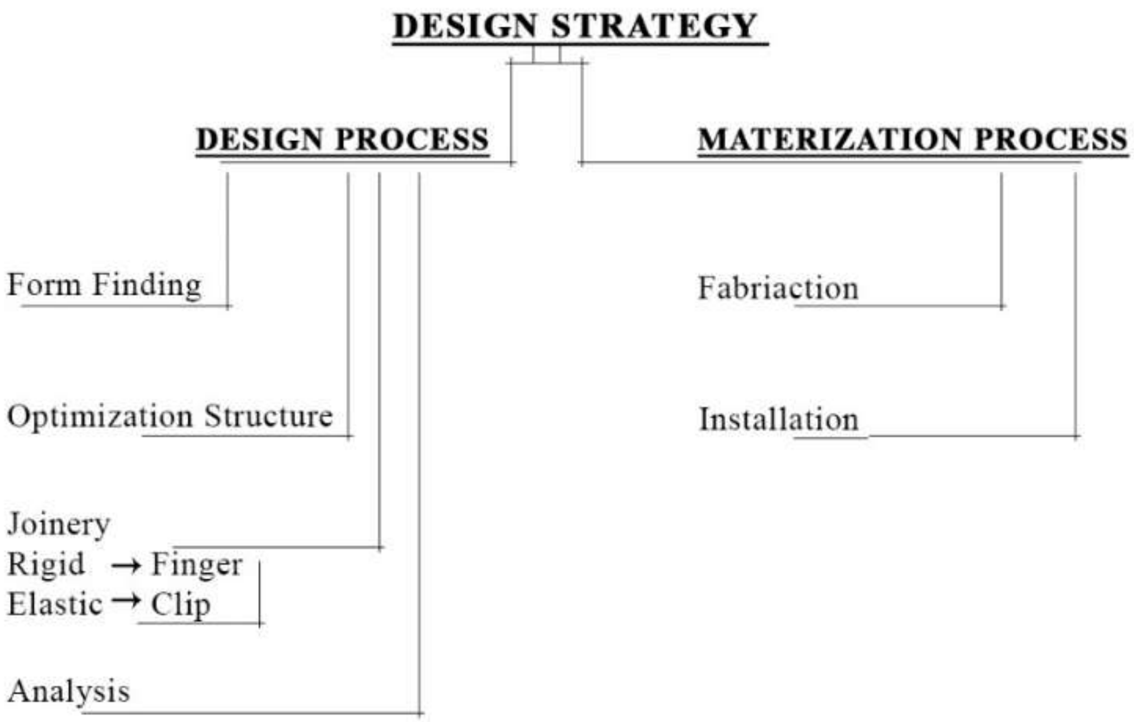


Figure 35 Design Strategy

The initial phase of the design process is the form-finding stage, which involves defining a structure's shape while considering geometric constraints and creating forms that are condition sized for specific forces. In the past, visual statics and hanging chains were used to define geometries, but digital tools have been developed recently to facilitate this process. Next, the starting surface is discretized using particles and springs, where each particle has vectors indicating its position, velocity, and forces. Finally, Hooke's law governs the interaction between the particles and springs.

This study focuses on positively curved shell structures, and evaluating curvature is essential in the planarization process. While concave panels with negative curvature can lead to significant deformations and self-intersections, positive curvatures result in better planarization outcomes.

However, when form-finding generates, and planarization is applied as a post-processing procedure, critical areas such as supports may cause the shell to deform. To address this, the proposed method integrates planarization into the form-finding process, introducing additional constraints to regulate planarization more rigorously, preventing extreme cell deformations. This can result in changes to the final shape, but it creates more efficient conditions with polygon vertices in a single plane, making them more accessible and complete to develop at a lower cost. (Sonntag et al. 2019)

In summary, the design process for shell structures typically begins with a form-finding phase that involves defining the structure's shape while considering geometrical constraints and the forces to which the structure will be subject. This is often done using digital tools that use particles and springs to discretize the surface and simulate its behavior. Planarization is a post-processing operation that can prevent deformations in important shell areas but may alter the final shape. Some techniques involve integrating planarization into the form-finding procedure to achieve more optimized shapes, which can be produced faster and at reduced costs. As a result, these techniques enable the development of efficient and reliable shell structures that can endure the expected loads and stresses.

4.3.5 The Shell Structure Development:

Designing a shell using triangulated geometry is a common approach to creating lightweight and robust structures. Triangulation involves dividing a surface into a series of triangles, which makes a strong and stable network of interconnected triangles. This technique is often used in engineering and architecture to design structures that withstand loads and stress.

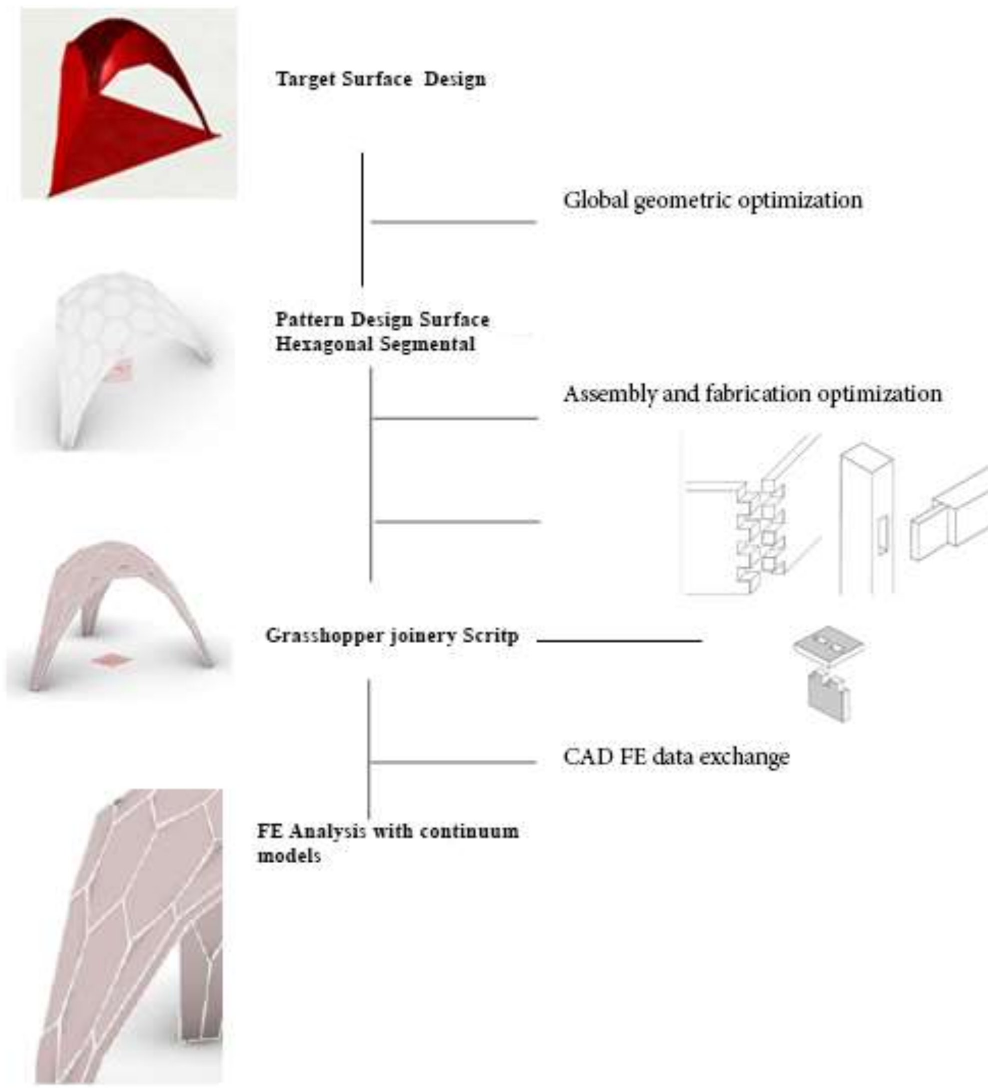


Figure 36 Shell Structure Development

Different rigid and elastic joinery techniques can be tested to create a rigid single-shell structure to find the best one. The joinery technique utilized will be determined by the unique requirements of the shell and the materials used.

Once the joinery technique is selected, the geometry of the shell can be optimized to ensure maximum rigidity and minimum weight. This can be achieved through computer modeling and simulation techniques, such as finite element analysis, which can help identify areas of high stress and deformation.

After optimizing the geometry, the digital model can create a physical prototype using additive manufacturing or other fabrication techniques. The final shell design should be as rigid as possible while still being as light as possible to ensure optimal performance and efficiency.

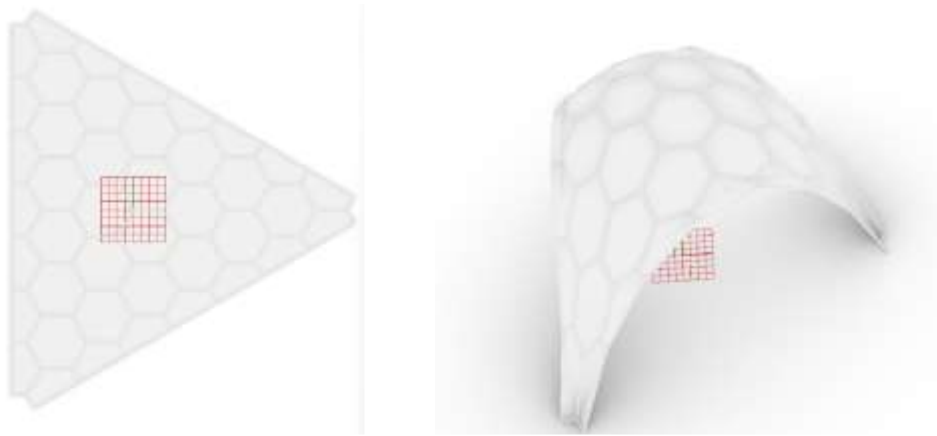


Figure 37 Planarization to Shell

Using Grasshopper and plugins like Ngon to generate various iterations of a shell mesh structure such as finger joinery. This involves creating a hexagonal mesh as the base and adjusting parameters in the Grasshopper script to optimize the form and generate different iterations.

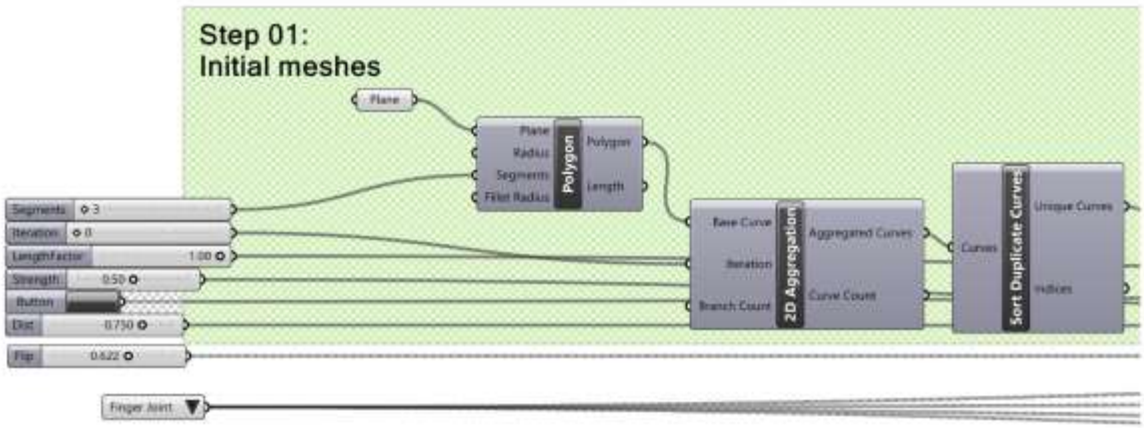


Figure 38 Initial Mesh Grasshopper Script

In the case of shell structures, this often involves finding the shape that can support the required loads with minimal material usage. Using Grasshopper and plugins like Ngon can help to automate and optimize this process, allowing for quick iteration and exploration of different forms. To start, create a hexagonal mesh in Grasshopper script using the appropriate tools and plugins. From there, adjust parameters such as the height and thickness of the shell, the spacing of the hexagonal cells, and the number of iterations to create different forms. As shown in the figure 38, these parameters can be adjusted manually or set up to automatically optimize based on specific design criteria, such as minimizing material usage or maximizing structural efficiency. By iterating through different forms and optimizing parameters, we eventually arrive at a form that meets the desired structural requirements while minimizing material usage and achieving other design goals. This process can be time-consuming and require some trial and error. However, Grasshopper and plugins like Ngon can help to streamline and automate the process, making it easier to explore different options and arrive at an optimal form.

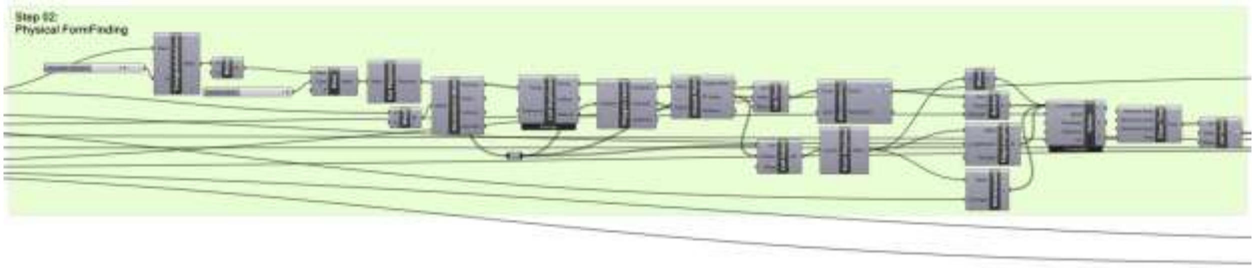


Figure 39 Physical Form Finding Grasshopper Script

A two-stage process for generating a shell mesh structure using Grasshopper.

In the first stage, Grasshopper would create an elemental hexagonal mesh plane. This Mesh would be the second stage's starting point for the physical form-finding process. This initial mesh plane can be made using various Grasshopper plugins, including Ngon. In the second stage, we would use Grasshopper to adjust the parameters of the hexagonal mesh plane to create the desired physical form of the shell structure. This involves modifying the thickness and height of the hexagonal cells to optimize the form and meet the desired structural requirements.

To achieve this, we would use Grasshopper to set up a parametric system that allows us to adjust these parameters dynamically. Changing the parameters' values can iteratively generate different forms of the shell structure, each with its own unique thickness and height configuration. This two-stage process allows the creation of a shell Mesh structure optimized in terms of its underlying geometry (i.e., the hexagonal mesh plane) and its physical form (i.e., the thickness and height of the cells). In addition, Grasshopper and various plugins can automate and streamline this process, making exploring and iterating distinctive design options easier.

The reason of the choosing the Particular hexagonal mesh is because of number of the reason such as Hexagons are a highly efficient shape when it comes to distributing forces evenly.

Each hexagon in a mesh structure shares its load with six surrounding hexagons, creating a strong and stable network. The hexagonal mesh pattern allows for a significant reduction in material usage compared to other structural configurations. The use of less material not only reduces costs but also minimizes the environmental impact of construction. The mesh structure's inherent strength-to-weight ratio makes it ideal for lightweight construction. It is commonly used in applications where weight reduction is important, such as large-span roofs, domes, and pavilions. Hexagonal shapes are prevalent in nature, from honeycombs to the cellular structure of plants and the basalt columns of Giant's Causeway. The use of hexagons in architecture and design can create a sense of harmony and visual connection with the natural world. Hexagonal mesh structures can be easily scaled up or down in size without losing their structural integrity. This scalability makes them adaptable to a wide range of applications, from small-scale temporary structures to large-scale permanent buildings. Overall, the hexagonal mesh shell structure combines structural efficiency, material savings, lightweight construction, natural integration, visual appeal, and scalability, making it a versatile and popular choice in architecture and design. Design the Shell for the basic the shell will be 2 ft by 3 ft for fabrication process and consist of the 41 Segments as the each segment is quite different form one another.

4.4 Optimization of the Basic Shell Mesh Geometry:

The shell is structure that must be carefully designed to avoid sensitivity to defects, as their form is critical to meet design constraints. This can be demonstrated through experiments or numerical simulations involving extensive deformation analysis. The research the Shape optimization is a more general concept that falls under structural optimization and should be used to aid the designer's intuition. The designer should also know that every design process component can affect the outcome. Experimental form-finding approaches and computer modeling can be helpful in preliminary design, while shape optimizations are more abstract and require a basic design to define the optimization problem. However, there is still much potential for design flexibility and creativity, and a hybrid of hanging membranes and form optimization is recommended for conceptual design, variation, and refinement. Despite significant improvements, there is no magical toolbox yet available. (Abramovic 2017)

A structural optimization is a powerful tool for minimizing some functional definitions of a structure's mechanical behavior. The idea of using optimization for form-finding in shell structures gained popularity in architecture. This technique involves shaping the structure through a process of structural optimization. It is like the automatic form-finding algorithms used in calculating tensile structures using the force density method. Optimization can handle various load scenarios or non-linear analysis, allowing it to overcome form-finding methods' limitations. (Mesnil et al., 2018)

Designers of shells can find inspiration from various sources. Still, Robert Hooke's principle offers a clear direction: forces should move towards the supports in axial compression with minimal bending, like an inverted chain. By extending Hooke's chain into a three-dimensional structure of elements and considering different support conditions, many compression-only shell forms can be created. Designers can construct more efficiently by reducing bending forces and thus make the most of limited resources. By comprehending and investigating the infinite possibilities for even the most constrained design problem, shell designers can continue to discover new shapes for generations. Masonry vault builders have uncovered several shell forms that operate under compression, as evidenced by the durability of these vaults, which will continue to impress future generations. Shell constructions, curved surface structures typically made of timber, concrete, metal, or masonry, embody this proof. The importance of computational approaches as a design tool for optimizing a timber complex structure construction is demonstrated. A typical topology optimization challenge entails spreading a specific material in a design domain subject to load and support criteria to maximize the structure's stiffness. (Fauche, Adriaenssens, and H. Prevost 2010)

Exploration of design space through structural optimization as shown in Fig 40 summarizes the three areas of structural optimization and how the suggested technique would solve them. First, the marionette approach is used to define geometry. The mechanical model uses the finite element technique to create e mechanical model. Finally, derivative-free techniques are used to find optima. Two families of exploration strategies are suggested to demonstrate the possibilities of Marionette meshes. The first family compares optimization outcomes for NURBS and Marionette methods using a single criterion, simplifying the comparison of design methodologies and helping deduce specific trends. The second family considers multiple optimization criteria, as engineers frequently face various constraints and conflicting aims in real-world projects. It is uncommon for systems to satisfy all optimization criteria, and designs based on Pareto fronts are preferred.

Global optimization is preferred for developing potentially innovative and efficient ideas in conceptual design.

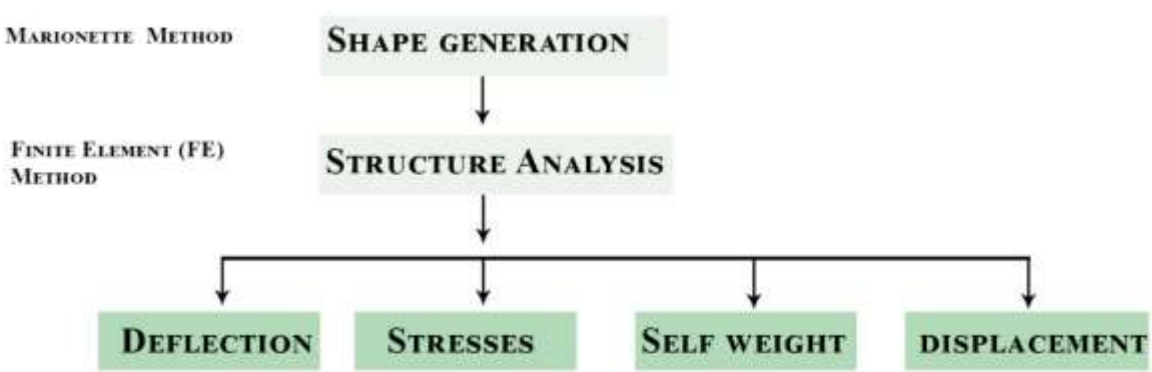


Figure 40 Framework for the Structure and Shape Optimization.

Determining the best shape for a shell based on specific limitations and goals is an optimization process typically done through trial and error, drawing from the designer's knowledge. To improve this process, it could be automated (as shown in Fig. 41. The optimization process involves three design processes - geometric and material design, analysis (including sensitivity), and mathematical optimization - repeated until the problem's constraints are met. The objectives of this optimization process can be traditional, such as minimizing weight or maximizing load-bearing capacity, which can cause buckling and material failure. Alternatively, the purposes can be stress-leveling, aiming for a uniform stress state, or minimizing strain energy, equivalent to maximizing stiffness.

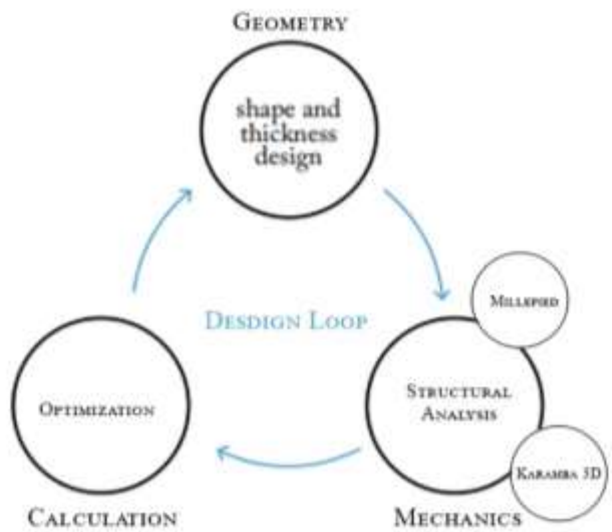


Figure 41 Shape Optimization Steps

The last parameter is an excellent objective for shells as it reduces bending and leads to a design that prioritizes the membrane. However, other goals may also be considered, such as enhancing toughness and ductility or avoiding specific frequency ranges. It is common to encounter conflicting situations, so a solution that balances multiple objectives must be found. The restrictions may include standard design constraints for stresses, displacements, and conditions on construction mass/weight or desired/unwanted frequencies. These limitations can be equality or soft constraints in the equilibrium equations. The design parameters may take various forms, including geometrical parameters that control the shell's shape and thickness during shape optimization. To locate all feasible solutions using the same geometric model, FE-based parameterization with filtering is the most suitable method for form-finding and early design. Changing the filter functions and sizes is an efficient approach to exploring the design space. The objective is to optimize the stiffness of a shell supported on three points and subject to self-weight. (Adriaenssens et al. 2014)

4.4.1 Grasshopper Script Basic Coding For Fem (Finite Element Method) Analysis:

The Grasshopper script is as follows: The writing begins by importing the Ngon plugin and creating a sphere. The "segment" command divides the globe into ten segments. The "shell" command is then used to create the primary form of the shell. The "optimize" command is then used to optimize the structure. The "kambra3d" and " Millipede" bases then process the script. The first part of the analysis is a FEM analysis using the Millepede plugin. The “Millepiede" command is used to create the study. The "shell" command is then used to create the primary form of the shell. The "optimize" command is then used to optimize the structure. The "kambra3d" and "millipede" commands are then used to process the script. The second part of the analysis is a structural analysis using Kambra 3D. The "kambra3d" command is used to create the analysis. The "shell" command is then used to create the primary form of the shell. The "optimize" command is then used to optimize the structure. The "kambra3d" and "millipede" commands are then used to process the script.

4.4.1.1 Millepiede

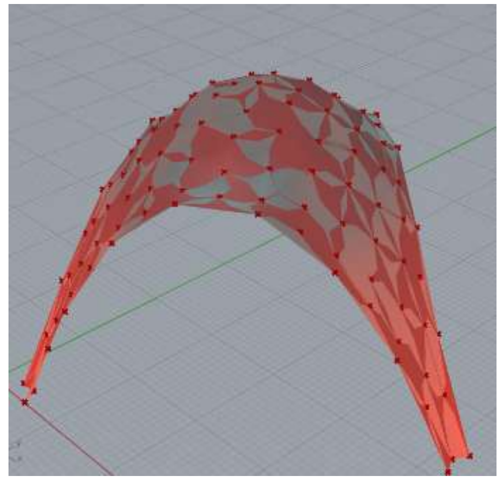


Figure 42 Basic Mesh Design

Millepede is a powerful tool for structural analysis and optimization of 3D frame and shell elements, 2D plate elements, and 3D volumetric elements. It is beneficial for quick linear elastic analysis and allows built-in topology optimization algorithms to help designers achieve optimal results with minimal effort. One of the key benefits of using Millipede is its ability to perform shape parametrization using Finite Element Methods. This approach maximizes the design space while minimizing the modeling phase's workload. In addition, the FE-mesh's nodes and ansatz functions are utilized as design variables and shape procedures, simplifying the design process significantly.

By specifying the coordinates of these nodes as design factors that alter the geometry, Millepede can efficiently analyze and optimize the structure's deflection and self-weight. The results can be retrieved and displayed in various ways, making it easier for designers to interpret and use the information to improve their designs. Overall, Millepede is a powerful tool that can help structural engineers and designers optimize their designs quickly and efficiently, leading to better and more cost-effective structures (Block, Lachauer, and Rippmann, 2014)

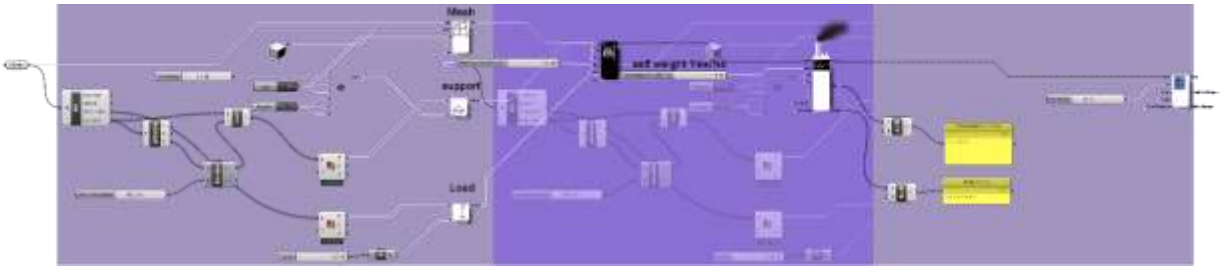


*Figure 43 Millipede Analysis Grasshopper Script**

The script runs and finds the deflection and the self-weight of the structure. Based on the information provided, self-weight can be calculated using a specified thickness and 12" thick wood weight for the proposed design. However, it is not clear how the weight is distributed throughout the structure or the total weight of the structure. Additionally, the figure provided shows a form diagram with point loads distributed based on tributary areas on the target. While this can be useful for analyzing the loads on the structure, it does not provide information about the self-weight or total weight of the structure. The deflection value of 0.0049" and importance of 6.2628e+7 (which I assume is in pounds) are also provided. However, it needs to be clarified what these values represent or how they relate to the self-weight or total weight of the structure. Overall, more information would be required to accurately calculate the self-weight of the proposed design and understand how the deflection and weight values relate to the overall structure.

---

*1 *Millipede Analysis Grasshopper script describe in the Appendices Section*

4.4.1.2 The Karamba 3D

The 3D Kambra shell element/face is used to optimize the design for less total displacement and weight. Millepede provides the optimized design's exact deflection and weight values. To add more detail to the design, the shape of the vault is specified by taking the best-fit thrust network computed in the previous phase and offsetting it by 12" on both sides. This approach ensures the structure is safe, provided a thrust network is inside the limits of its geometry for all additional loading instances. There may be many additional loading scenarios in an actual project. Therefore, it is essential to thoroughly analyze and optimize the design using tools like Millipede and 3D Kambra to ensure that it can withstand various loading conditions while minimizing displacement and weight.

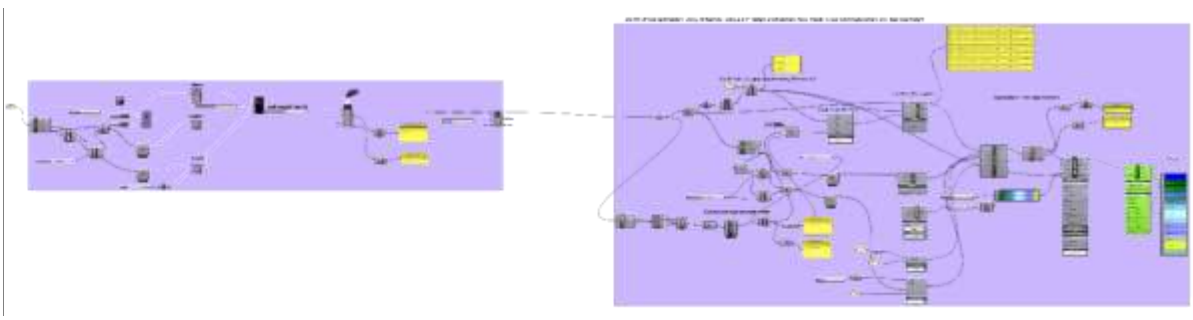


Figure 44 Kambra 3D Grasshopper Script

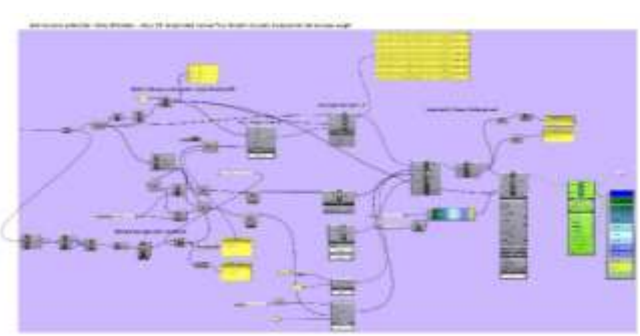


Figure 46 Finite Element Method Analysis Kambra 3D GH Script

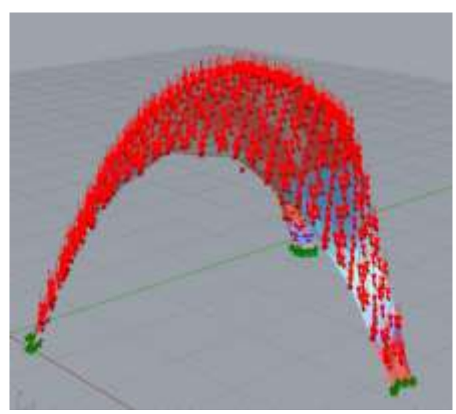


Figure 45 Applying the Load Gravity Load

**Kambra 3D Grasshopper script and *Finite Element Method Analysis Kambra 3D GH script 2 & 3*

The stress and the displacement etc., are as follows.

Displacement in cm

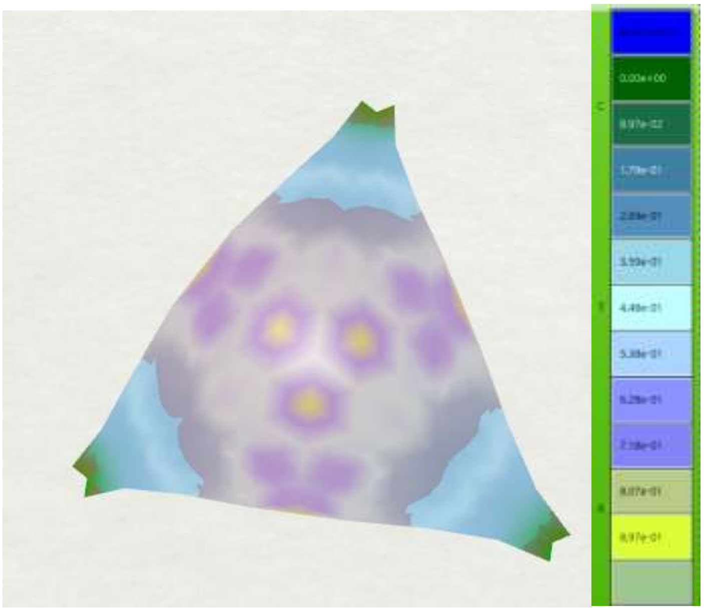


Figure 47 Displacement Values in cm

Panic -Stress 1 Tensile in KN/cm2

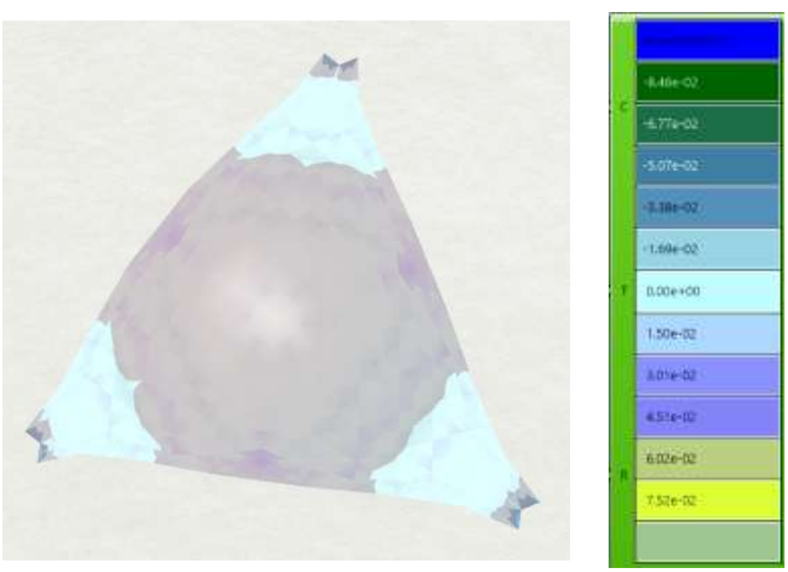


Figure 48 Stress 1 Tensile In KN/cm2 on Mesh

Panic stress2 compressive KN/cm2

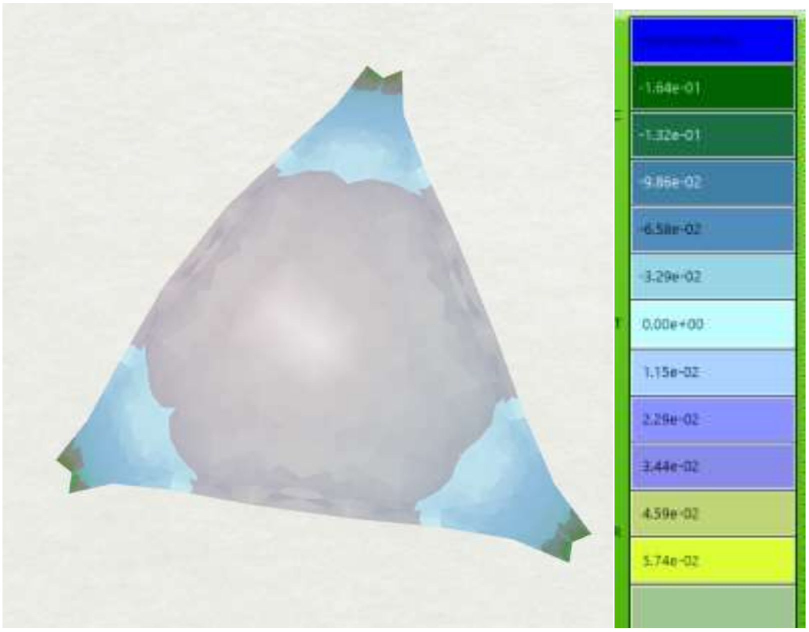


Figure 49 stress2 Compressive KN/cm2

Equivalent Stress KN/cm2

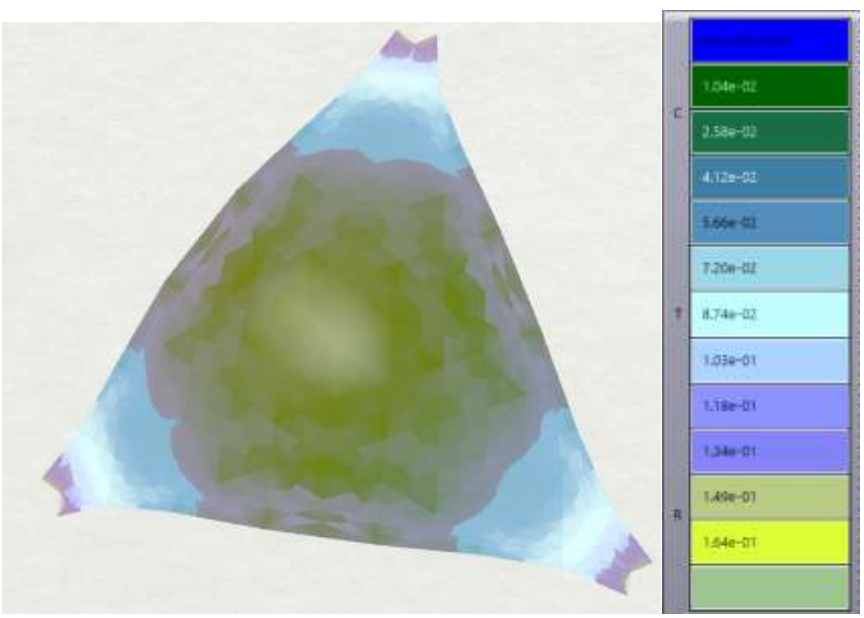


Figure 50 Equivalent Stress KN/cm2

4.5 Conclusion:

This provides a guide on performing a Finite Element Method (FEM) structure analysis on a target surface with a specific set of loads. The analysis is organized as a series of optimization problems, and efficient solving strategies are employed for each. This process assesses the structural feasibility of a complex and geometrically planned vaulted timber construction. The structure is analyzed under its self-weight, and a target geometry is derived from the results. The safety of this target geometry is then evaluated under various loading scenarios. This approach is like assessing a design concept, ensuring the final structure is safe and efficient.

Optimization techniques such as Millepede and 3D Kambra minimize displacement and weight while ensuring structural safety under different loading conditions. This is a vital aspect of engineering and construction as it guarantees that the final structure meets all requirements and is safe. In conclusion, the chapter demonstrates how FEM analysis, optimization methods, and efficient solving strategies can be used to assess the structural viability of complex and geometrically planned timber constructions. This approach helps engineers and designers create safe, efficient structures that meet all requirements.

Chapter 5

5.1 Process of creating joinery:

Joinery refers to the connections between the individual components of the shell structure, which can be either rigid or elastic depending on the design requirements. To create joinery on the selected shell surface, first, we need to determine the type of joinery required based on the design criteria. Once the type of joinery is established, choose one of the three main joinery types, which are:

- **Finger joinery** involves connecting two shell mesh structure components along their edges. Finger joinery is typically rigid, not allowing movement between the components.
- **Clip and half lap joint:** This type of joinery involves using clips to connect the components of the shell mesh structure. The pins are typically connected to the other segment. Clip and Tenon joinery are under the category of elastic joinery. Some degree of movement or flexibility between the components makes them ideal for structures that may experience stress or movement.
- **Tenon and mortise:** This type of joinery involves using flexible joints, such as the Tenon joint or tongue and groove for board structure, to connect the components of the shell mesh segmental structure. Adjustable joints allow some degree of movement or flexibility between the elements, making them ideal for structures that may experience stress or movement.

Once the type of joinery is established, use Grasshopper to optimize and project the joinery onto the selected surface of the shell structure. This involves analyzing the algorithmic behavior of the Grasshopper script to ensure that the joinery is created as efficiently and effectively as possible. It is important to note that there is no one-size-fits-all approach to creating joinery for shell mesh structures. The type of joinery required will depend on the specific design requirements, and different techniques may need to be employed to achieve the desired result. However, selecting the appropriate type of joinery and optimizing the Grasshopper script can create a robust and effective shell mesh structure that meets the desired design criteria.

5.2 The Finger Joinery

The design starts from nothing using the five steps to generate the parametric finger joinery. Testing the effectiveness of a shell structure with three supports as part of the thesis project's further development. Even though they tend to disintegrate and offer no structural support for the whole model, a medial spine facilitates assembly. Once it is completed, all other components are attached.

i. **Initial Mesh:**

The initial plane surface is generated and converted into the Mesh in the first phase. Then, the segmental of the plane is parametrically controlled and adjusted accordingly. Using the three segments is the most basic and minimal approach for the form of the Basic shell tessellation of symmetrical hexagonal shape. For further research, it will be parametrically adjusted accordingly and further designed.

ii. **Physical forms finding**

The second step is the form finding which create the form and Mesh to create the parametric geometry. The basic geometry mesh is triangular, and the Mesh targeted shape is Hexagonal.

When dealing with symmetrical shapes, Grasshopper can automate the process. However, working with asymmetrical shapes requires background knowledge in topics such as the medial spine, force flow in discrete element shell geometry, and the size of individual voussoirs.

Currently, these shapes are created manually due to the difficulty of maintaining an equal number of vertices in each detail. This results in an N-Gon pattern for the entire tessellation. Currently, these shapes are created manually due to the difficulty of maintaining an equal number of vertices in each detail. This results in an N-Gon pattern for the entire tessellation.

iii. **Simplify & Unify Windings of Mesh**

The 3rd step is simplifying and unifying the winging of the Mesh from the second step. as the Mesh is designed.

iv. **Planarize Finger Joint Mesh**

The 4th step is to create the finger joinery using the NGon plugin to create the parametric finger joinery on the hexagonal surface.

v. **Solid Mesh**

The 5th step converted the Mesh into sold create, the mitered joinery to expect a solid form.

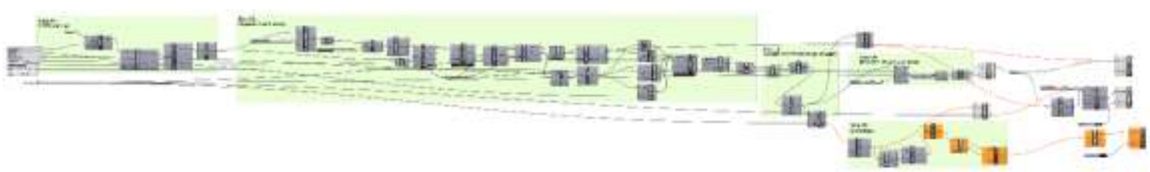


*Figure 51 Finger Joinery Grasshopper Script**

*4 *Finger joinery Grasshopper Script*describe in the Appendices Section*

Figure 53 Finger Segmental Shell

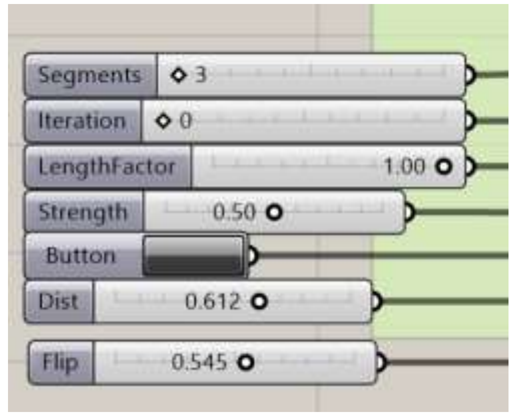


Figure 52 Parameters to Adjust the Finger Joinery

The specific parameter is developed to control the segments; length controls the plane length, iteration, and distance using the finger length, length factor, and the Flip factor, which contains the finger distance. The sheet will be a single shell. More depth must be in the single and not too much depth.

vi. **Fabrication setup:**

For the fabrication, the mesh is set up from the previous one. The load is less on the script. The separate and pen nest plugin is used to create the line for the laser cutting or CNC.

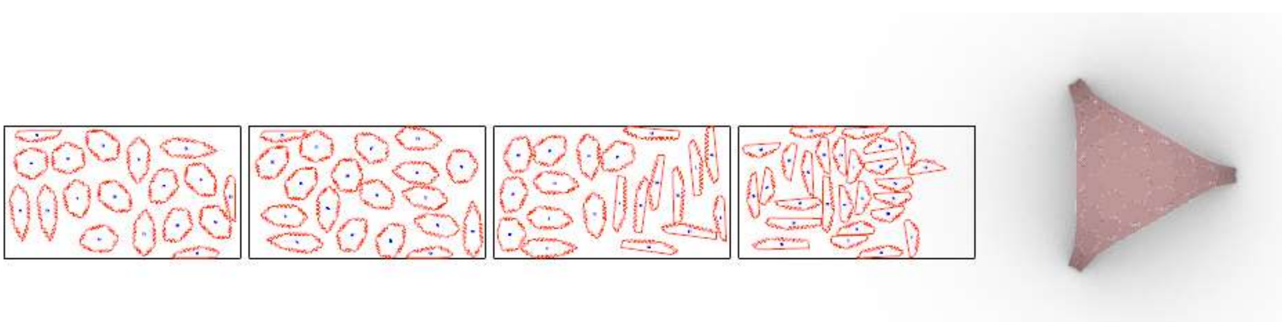


Figure 54 Preparing For Fabrication

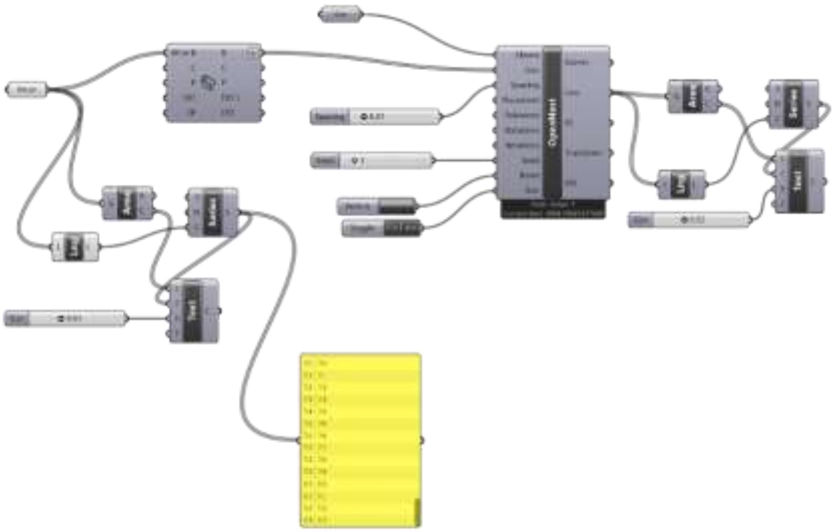


Figure 55 Open Nest Script For Fabrication

5.3 Halved and Lap Clip Joint

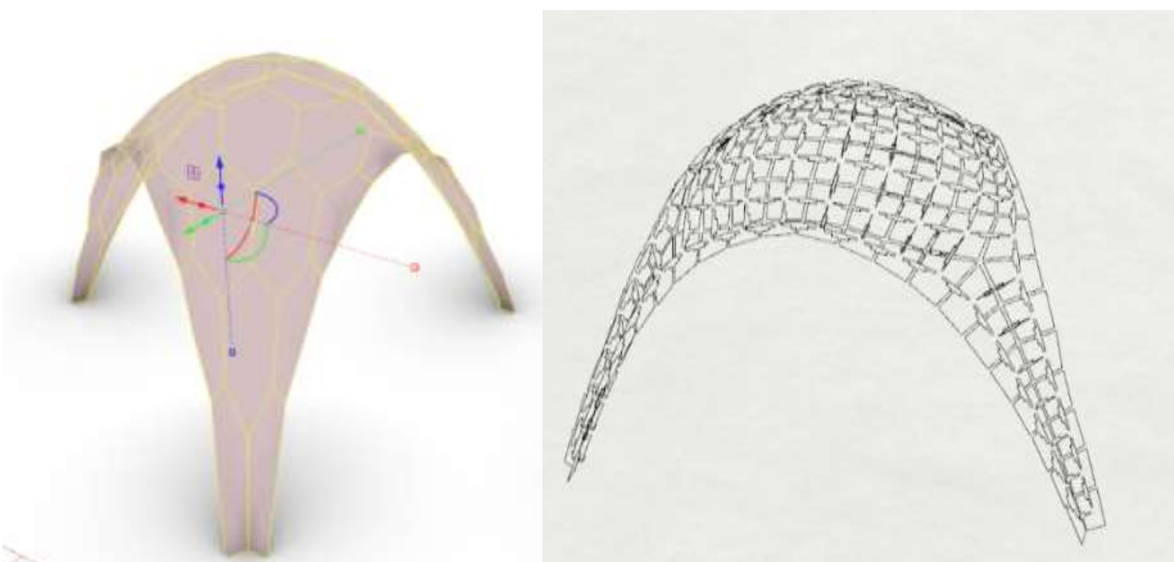


Figure 56 Mesh to Triangular Halved Lap Clip Joint

The second iteration structure is based on the same shell structure. Again, the basic shell mesh is converted into the Brep surface and the Grasshopper. This iteration converts the first one from the Mesh to the Brep.

Figure 57 Detail of the Clip and Segment

*Figure 58 Halved and Lap Clip Joinery Script **

The next step is to create the designed clips, and joinery is projected on the Berp/ surface. The Mesh joinery forms the basic geometry as the base experiment converting the Mesh into the triangular character, which acts as the Berp. The detailed Grasshopper script is developed where Berp has the variation, and the other is designed as the main script.

*5 * Halved and Lap Clip Joinery Script Describe in Appendices Section*

5.4 The Tenon and Mortise joint

In the finger joinery using the shell tessellation of symmetrical hexagonal structure, the finger joinery is created, and the shell form is derived form. For the rigid wooden joinery, the 2nd iteration will be designed. The Tenon and Mortise joint have a depth and a double shell structure. The depth is crucial for them to create the most sustainable Tenon. The previous Mesh is converted in the Surface, creating a separate Grasshopper script. They use the same open nest and NGon plugin to develop the joinery.

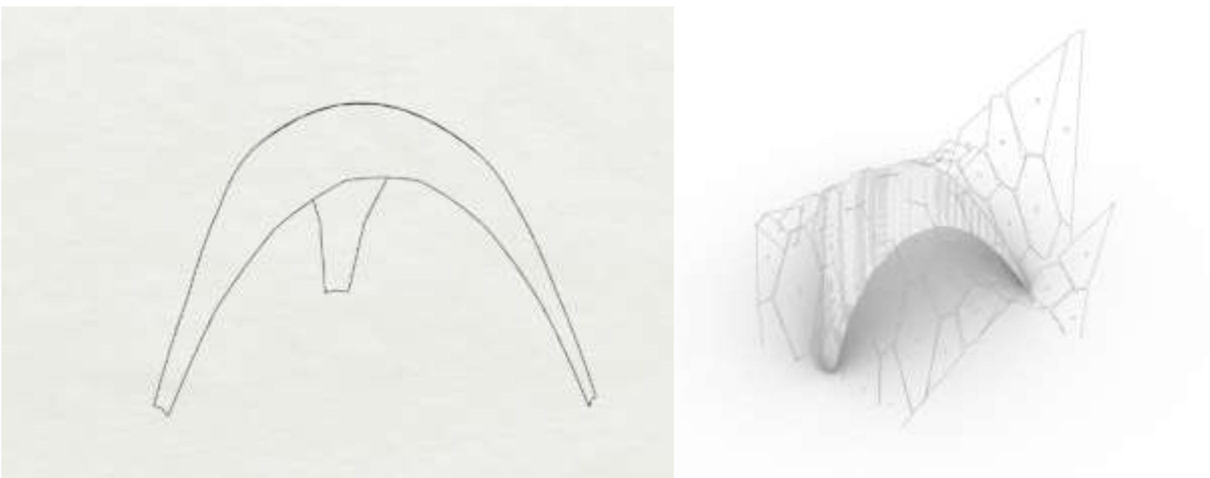


Figure 59 Tenon and Mortise Joint Mesh to Joinery

The iteration of the Tenon and the Mortise joint remains the same. The other issue is that it did not apply to the filling groove. The Tenon and Mortise are not fabricated in this research as the fabrication requires other methods, and CNC milling is limited to only 3-axis machines.

5.5 Conclusion

In hexagonal tessellations, self-interlocking is more noticeable when in motion. When applying a hexagonal bond tessellation to stack quadrilaterals, stripes with convex curvature separate by forming arches. The issue is resolved for concave-convex curvature due to applied forces on the side stripes. The compression-only behavior of structures is influenced by the degree of curvature or angle between its elements. With a concave curvature, the hexagonal pattern resembles a quadrilateral. With increased curvature, the hexagon may take on a ribbon-like shape, bending inward towards the plane. The subsequent phase focuses on examining the effects of variables like tessellation pattern and thickness on single and double curvature, particularly in intricate geometries such as domes. The goal is to determine the optimal combination of these variables to achieve desired outcomes.

5.6 Final Fabrication Process:

After completing the three basic iterations in creating a parametric finger joinery for a shell structure, two iterations have been selected for the fabrication process. These two iterations were chosen based on the nature of the joinery, which can be divided into elastic and rigid joinery.

Both elastic and rigid geometry were experimented with to determine which type of joinery is used , they were then projected onto the simple iteration of the targeted geometry (geometry derived form the computational approach) from there, the effectiveness of each type of joinery in terms of their ability to provide structural support, ease of fabrication, and overall aesthetic appeal.

Elastic joinery typically refers to connections that allow some flexibility or movement, while rigid wooden joinery involves fixed connections that do not qualify for movement. The effectiveness of each type of joinery may vary depending on the materials, intended use of the structure, and design objectives. As a result, the decision to use one type over the other can be influenced by several factors.

5.7 Fabrication process CNC milling:

The thesis proposed a method that utilizes digital tools, including parametric modeling and Grasshopper® functions, for designing a shell structure. The primary objective was to optimize the construction process by integrating planarization and creating a connection system that simplifies the final assembly. The process involved using a form-finding technique to produce a shell based on a hexagonal subdivision, which was then refined using a planarization simulation to minimize possible geometric distortions. Finite Element Analysis evaluated the structural efficiency, emphasizing material properties and compression. Lastly, a tessellation process was employed to construct hexagonal panels and a puzzle-like connection system that meets specific structural and fabrication requirements. Overall, this research underscores the benefits of digital tools in streamlining the design and fabrication of intricate structures while ensuring the desired structural efficiency. Using parametric modeling and simulation, the design can be optimized for structural performance while also simplifying the fabrication process through a puzzle-like connection system. In addition, finite Element Analysis allows a more accurate assessment of the structure's strength and behavior, which can inform design decisions and material selection. Overall, this digital process offers a more efficient and effective way to design and build complex structures.

“So, verily, with every difficulty, there is relief.”

“Verily, with every difficulty, there is a relief.”

[94:6] Quran

Chapter 6

6.1 From Digital to Physical:

The last chapter, Details the study of the digital form finding and the joinery on the targeted mesh. This chapter will explain the detailed fabrication process using CNC milling and the two-design iteration of rigid Finger and Elastic clip joinery. As for the last joinery, the Tenon and mortise joint is not fabricated in this part of the research. It will be done in future research using advanced fabrication techniques.

This chapter will focus on the fabrication process using CNC milling and the two design iterations of the Finger and Elastic clip joinery.

- **Design Iteration 1: Rigid Finger Joinery**

The first design iteration is a rigid Finger joinery. The Finger joint is a popular joinery method commonly used in woodworking. The joint consists of two interlocking pieces that fit together tightly. The joint is strong and rigid, making it ideal for structural applications.

The Finger joinery was designed to be cut using CNC milling. From the foam prototype, the joinery was refined, and the final design was cut from MDF. Then, to form a small cube, the MDF pieces were assembled.

The Finger joinery was successful, and the cube was rigid and stable. However, the joint required much precision in the cutting and assembly process. As a result, the joint was difficult to assemble correctly, and the tolerance between the pieces was tight, making it challenging to fit them together.

- **Design Iteration 2: Elastic Clip Joinery**

The second design iteration is an Elastic Clip joinery. The Elastic clip joint is a simple joinery method that uses an elastic clip to hold two pieces of material together. The joint is easy to assemble, and the clip allows flexibility. The Elastic Clip joinery was designed to be cut using CNC milling. The joinery was refined using the foam prototype, and the final design was cut from a block of MDF. The MDF pieces were then assembled to form a small cube. The Elastic Clip joinery was successful, and the cube was stable and easy to make. The joint required less precision in the cutting and assembly process, and the clip allowed for some flexibility in the joint.

6.2 Porotype Testing:

Computer Numerical Control CNC Milling:

Figure 60 Kansas State University

Figure 61 CNC Router Machine

The router-cut version does not work because the radius corners collide, and the part edges do not align. While cutting each slot deeper is possible, this can result in a void in the joint's center and stress concentrated on the rounded corners. A better solution is to match the inside faces of the edge laps perfectly, which results in visible round divots in the assembled joint.

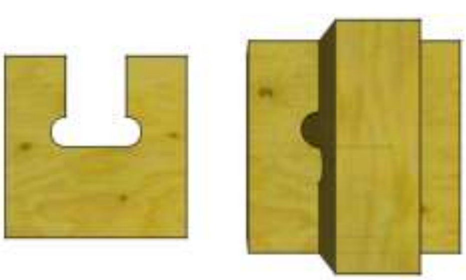


Figure 62 Dog Bone Cut

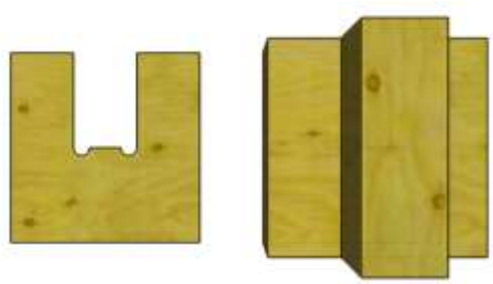


Figure 63 U Shape Cut

6.3 The Prototype Test:

For the first test, the MDF ½" is CNC, and the surprising results are obtained, which are described as follows

6.3.1 The Rigid Joinery: Finger Joinery

This section will discuss the observations and errors encountered during the hexagonal shell fabrication process using the Ngon joinery. Specifically, we will focus on the differences and similarities between the digital and physical approaches for the bottom and core-shell parts.

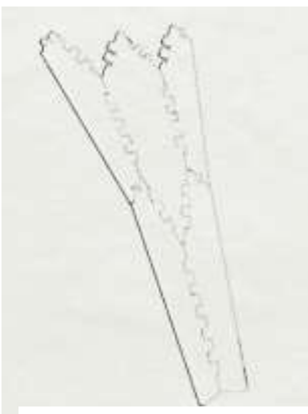


Figure 65 Bottom Piece

Figure 64 CENTRAL CORE

❖ **Bottom Part of the Shell:**

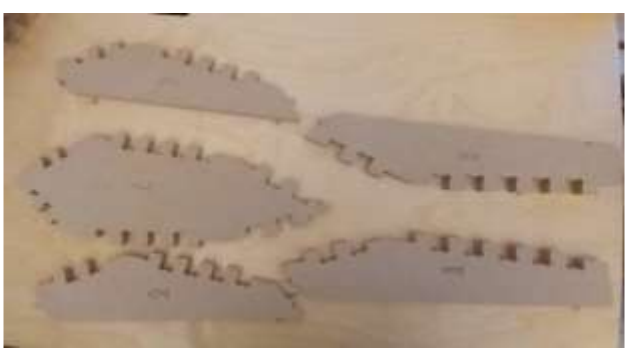


Figure 67 Base Segment

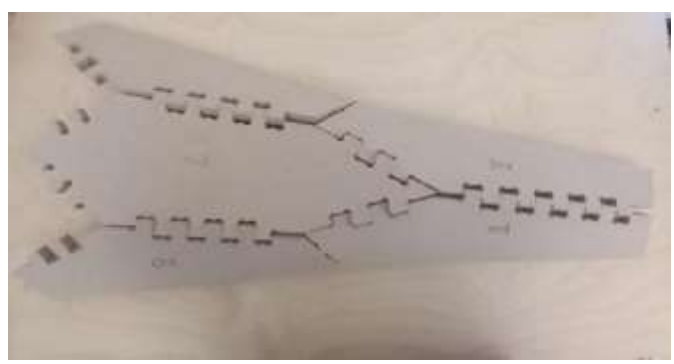


Figure 66 Assembly

The bottom part of the shell was fabricated using the Ngon joinery and ½" MDF. The digital and physical approaches were quite similar, as the joinery was designed to be rigid and stable. The bottom part of the shell did not present any significant errors or observations. The fingers are connected well and inflexible, and the side segment joinery is substantial, as red to the middle part, which is weak because the segments are not joined perfectly.

Figure 68 Digital to Physical

- ❖ **Core-Shell Part of the Shell:**

Figure 69 Core Reality of Digital

The core-shell part of the shell was also fabricated using the Ngon joinery and ½" MDF. The digital and physical approaches were similar, but some errors were encountered during the fabrication process joinery for the finger joints was designed to be rigid. Still, the faces on the sides were at 90-degree angles, which made it structurally unstable.

For the next prototype, the side angles of the finger joints should be adjusted so that the fingers are connected perfectly, without any gaps or spaces that can make the joint unstable. This observation highlights the importance of testing and refining the design through iterative prototyping. The digital design may look sound, but only through physical testing can errors and improvements be identified.

In this section, we have discussed the observations and errors encountered during the fabrication process of the hexagonal shell using the Ngon joinery. It’s noted that the digital and physical approaches were similar. However, errors were discovered during the core-shell part fabrication due to the finger joinery's rigidity. It emphasized the importance of testing and refining the design through iterative prototyping.

6.3.2 Elastic Joinery (The Halved and Lapped Clip Joinery)

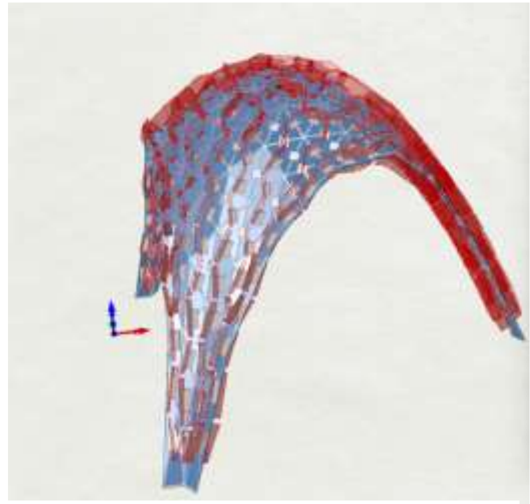


Figure 70 Clip Triangle Segment Shell

This section, will discuss the observations and errors encountered during the digital design and prototype of the elastic clip joinery for the hexagonal shell. Specifically, focus on the mesh design, material properties, and errors encountered during the prototype phase. The hexagonal shape of the shell was discretized into a mesh, with each mesh face representing a timber panel. To ensure planarity and constant thickness, hexagonal patterns with trivalent vertices were used. However, during the fabrication of the elastic clip joinery, it was observed that the mesh and triangulation mesh division was too small for CNC milling. This design was less compatible with CNC milling, limiting the ability to fabricate the shell parts accurately. As a result, the design profile had to be changed to make it identical to the rigid joinery profile, which was more suitable for CNC milling.

During the prototype phase, it was observed that the material properties of the timber panels influenced the curvature of the segmental assembly. Therefore, elastic clip joinery had to provide enough flexibility to accommodate the natural curvature of timber panels. This observation highlights the importance of selecting appropriate materials for timber structures and considering their material properties during the design phase.

*Figure 71 Halved And Lapped Clip Joinery Grasshopper Script**

The details Grasshopper script described above show the exact method of design.

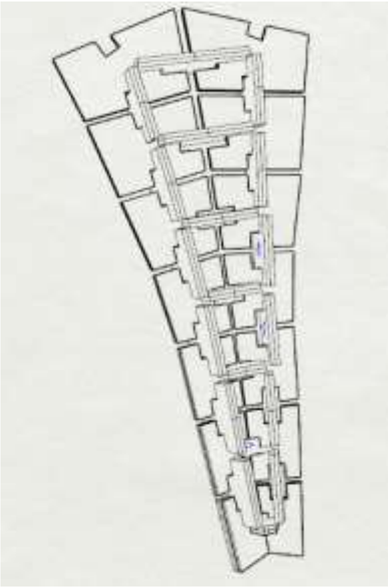


Figure 73 Segmental Digital

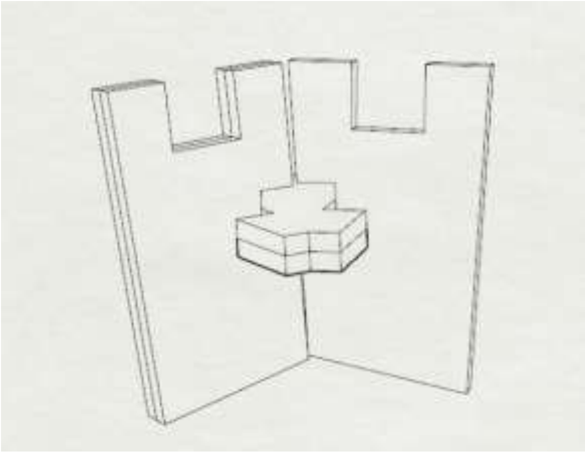


Figure 72 Detail Clip Joins Two Segments

The prototype digital overall and the signal piece

the ½" offset make the clip work perfectly and digitally joins the segments.

*5 * Halved and lap clip joinery script describe in Appendices Section*

Figure 74 The Segments

The 15 segments of the clips and the joineries are 2’4” long.

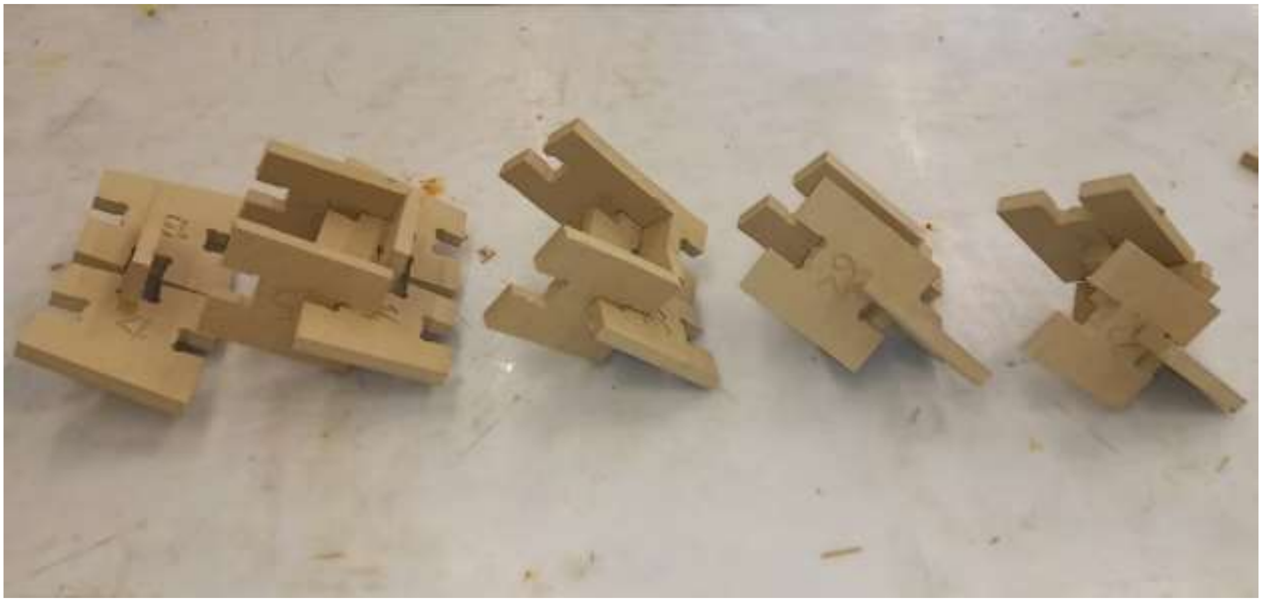


Figure 75 Assembly Process

The first small segmental is connected, and then five pieces are connected to complete the assembly.

Figure 76 Shows The Digital Reality of The Segment.

During the prototype phase, it was discovered that there was an error in the thickness of the clips and segments, which was not provided in the digital design phase. This error resulted in an inaccurate prototype, highlighting the importance of including all relevant information in the digital design phase to ensure accurate prototyping.

In this section, discussed the observations and errors encountered during the digital design and prototype of the elastic clip joinery for the hexagonal shell. We emphasized the importance of selecting appropriate materials and considering their material properties during the design phase. Additionally, we highlighted the importance of including all relevant information in the digital design phase to ensure accurate prototyping, as errors in thickness or other design parameters can significantly impact the accuracy of the physical prototype as this one too many segments make it unstable. Finally, we noted that the design profile had to be changed to make it more suitable for CNC milling, which allowed for the accurate fabrication of the shell parts.

Chapter 7

7.1 Final Assembly and Fabrication:

The chapter details the modifications made to the prototype testing of finger and clip joinery and the subsequent resolution of errors identified in the previous prototype.

7.1.1 Semi Curve Finger Joinery Prototype 2

creating the second prototype involves assembling smaller parts to create the overall design and identifying errors. The half shell segments were CNC-cut from 1/2-inch MDF to expedite the assembly process and scaled down by half. The parameters used for this prototype are as follows. Instead of using the dog bone cut from the previous prototype, a U-shape option was explored, which resulted in a notable

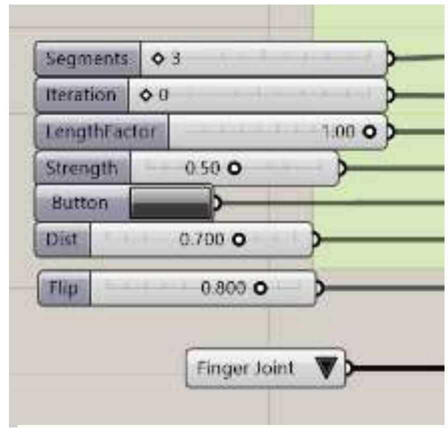


Figure 77 Adjust Parameter

change in the assembly method. The second prototype was created by assembling smaller parts to form the overall design and identifying errors. Half shell segments were CNC-cut from 1/2-inch MDF to streamline the assembly process and reduced by half. The prototype's parameters are listed below. The assembly method was significantly impacted by using a U-shape option instead of the dog bone cut used in the previous prototype.

7.1.2 Observation:

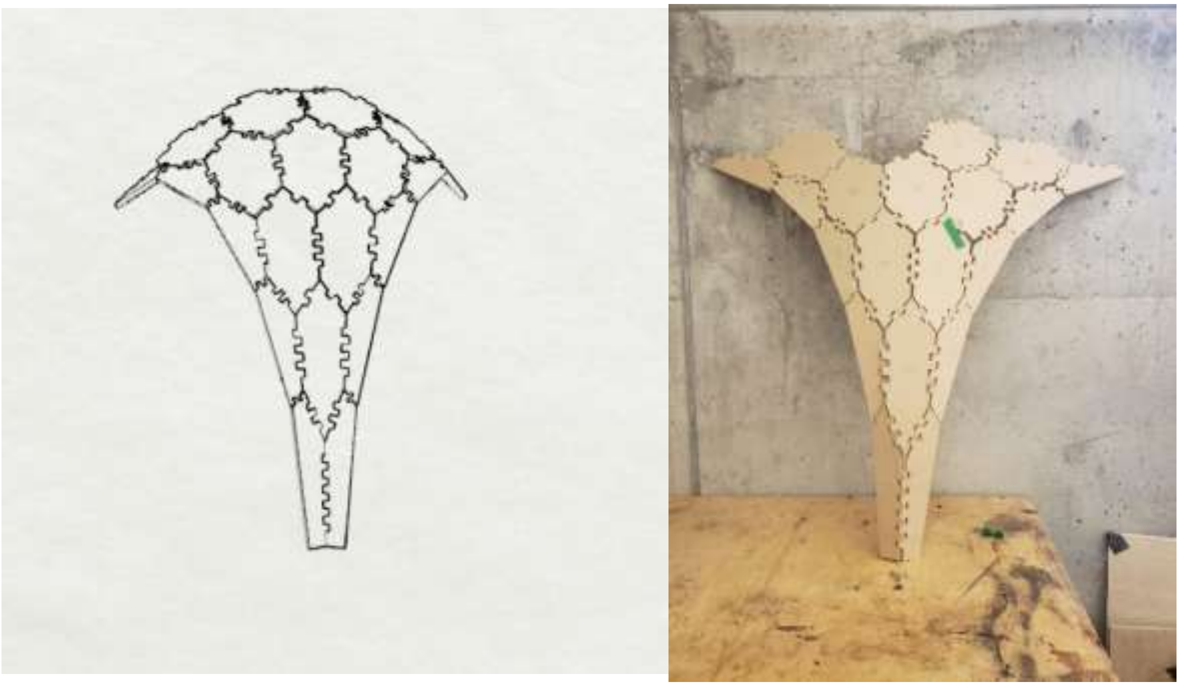


Figure 78 Prototype 2 Adjustment in Joinery and Fabrication

On a larger scale, the central core of the prototype is unstable. To create tolerance, the fingers are filled with timber filler for the experiment. However, adjusting the finger joinery is difficult due to the straight edges. As the fingers join from bottom to top, the upper joinery is segmental, and challenging to achieve the required curvature. The research objective requires no external support for the self-weighted shell. However, the intersection of the segments creates a gap due to the right angle of the elements, which is between ¼" to 1/8". This gap creates load compression and tension, making the structure less stable, especially the central part, as observed in the structural optimization. The proper angle cut of the fingers makes it difficult to attach them, especially in the central core, which overlaps. As the shell curves, the edges become even more challenging to secure. The segments are straight because of the 3-axis CNC, which makes it difficult to achieve a greater curvature, unlike multi-axis, which would make assembly easier. Some segments are not fixed correctly because of the curve, and this prototype provides observations for the final prototype. The edges of the shell should connect plainly without any joinery, as joinery can create issues. The two sides of the surface are already connected perfectly so that the edge-to-edge connection can be ignored. Manual adjustments, such as central segment nodes and edge adjustments, should be made before the final prototype test. The main core stiffness of the wood creates issues while connecting other segments, which need to be addressed. The shell is flexible, but the curvature needs adjustment from plain to curve

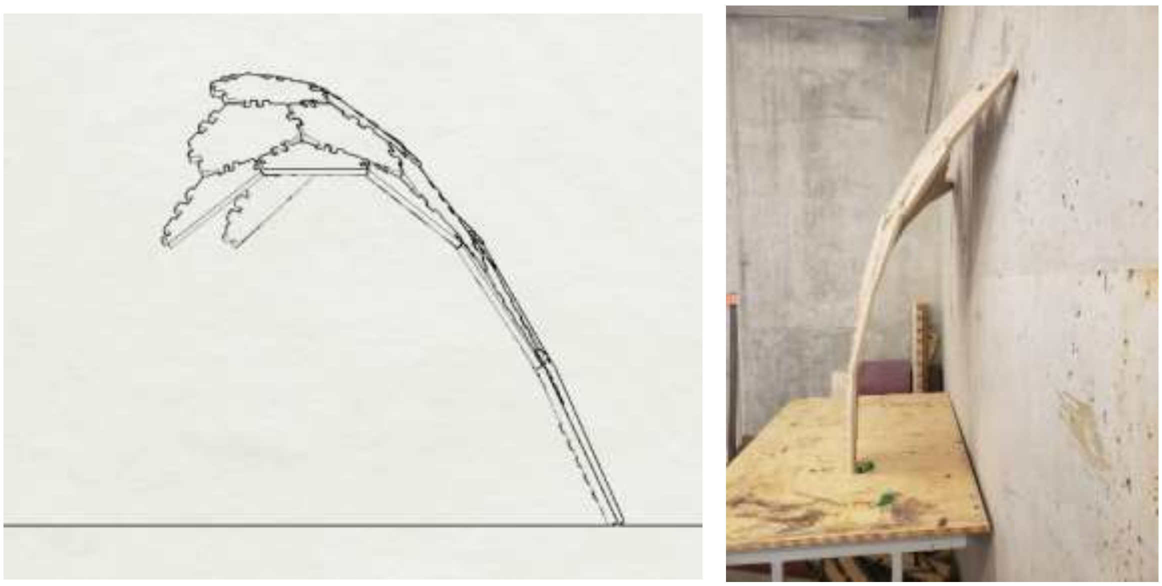


Figure 79 Curvature of the Shell

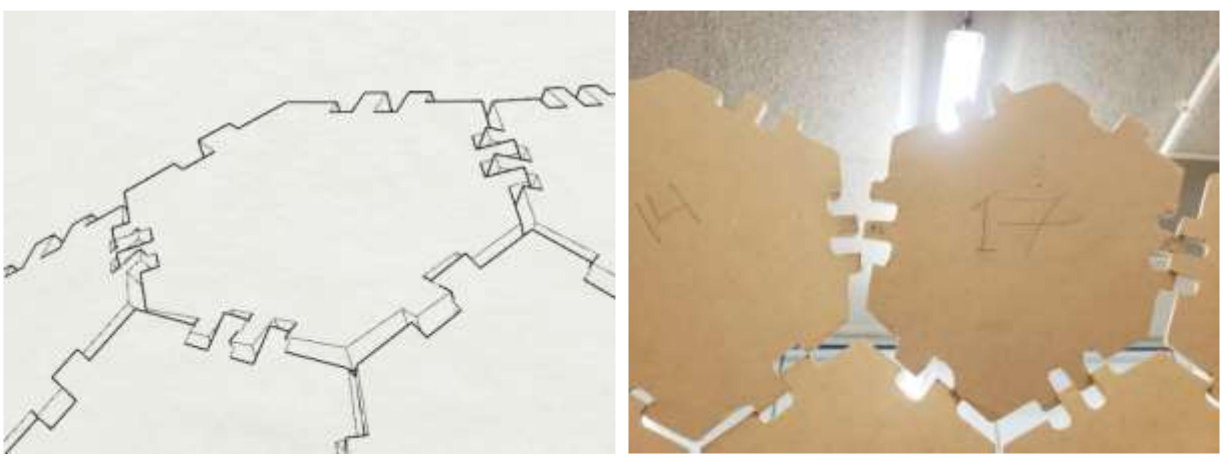


Figure 80 Central Core Curvature

Figure 81 Gap between Segments

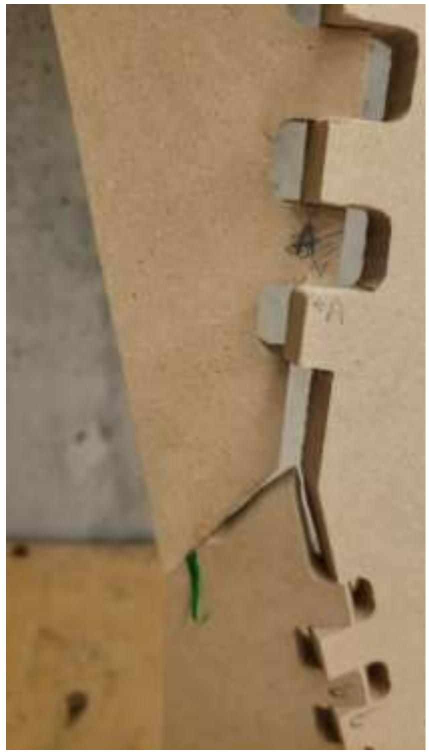


Figure 82 Edges Finger Not Fit Accordingly

Figure 83 Edges Adjustment

Figure 84 Tension And Gap on the Finger

Figure 85 Center Gap in Segmental Problem

A slight change in the digital to material is the bending of the curvature because of the nature of finger joinery in the shell. The errors are deductible, and the adjustment is set for the final prototype test.

7.2 Final Prototype Test:

The final test parameter is adjusted for the final prototype will discussed in the following sections, the edges joinery is changed, and the finger distance is adjusted. Furthermore, for the clip joinery, the revision of the script is done. To make the design unified and harmonious.

7.2.1 The Halved and Lapped Clip Joinery (Elastic Joinery):

Design harmony refers to the coherence and balance between distinctive design elements. The design follows a hexagonal base geometry like the clip joints in this case. The hexagonal plates provide elasticity, and CNC is used to cut the design using ½" MDF segments with straight profile clips to simplify the procedure. The base and core fit well, but the full-scale assembly faced issues due to the weight of the timber and the material's nature. As the clips are smaller and the surface area is big so it does not fir correctly.

*Figure 81 Hexagonal Halved and Clip Joint **

*6 * Hexagonal Halved and Clip Joint Describes In Appendices Section*

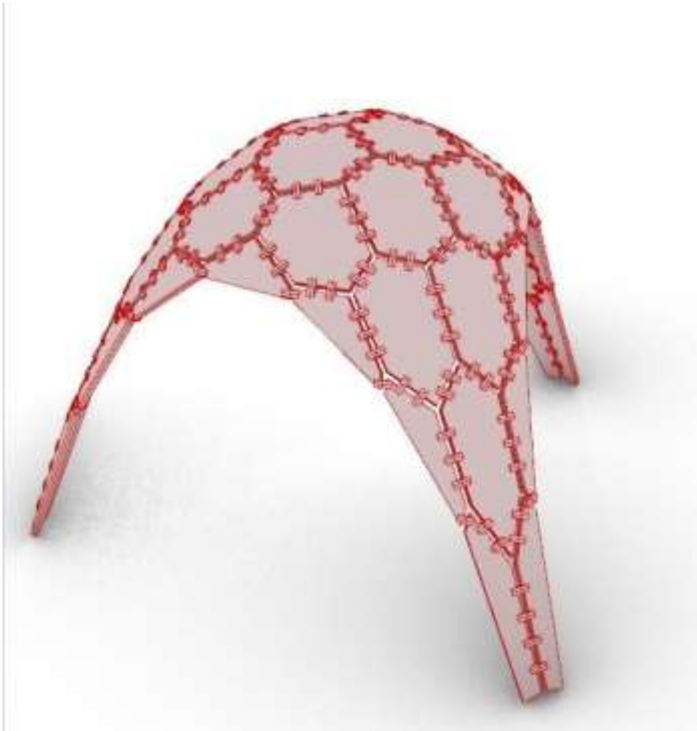


Figure 82 Halved and Lapped Clip Joint

Figure 83 CNC Milled

The design harmony involves the balance between design elements. The design follows a hexagonal base like the clip joints and uses CNC to cut ½" MDF segments with straight profile clips for a more straightforward design.

Figure 85 Base Joinery

Figure 84 Center Core

To resolve this, the small-scale prototype was replicated using laser cutting and a 3Axis CNC machine, and the segments were assembled ideally using two-ply sheet material. While the clip works well and the elasticity depends on the material nature, stability requires an external structure, and the instability causes issues in the full-scale assembly.

The full-scale assembly faced issues due to the weight of the timber and its material nature and the clip cuts are smaller and the surface areas are larger so it make instability in the structure.

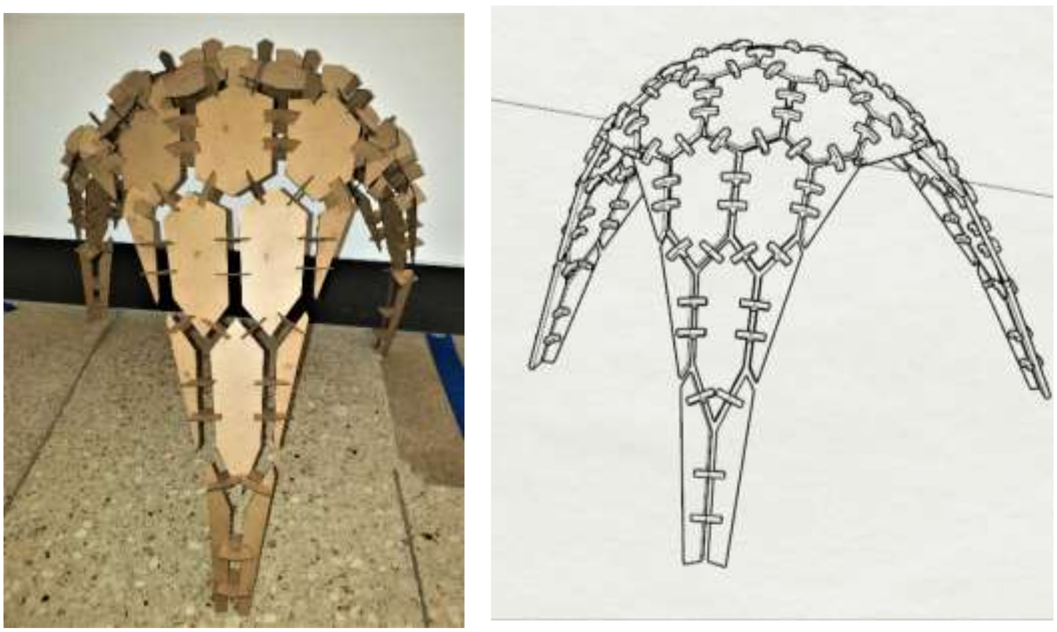


Figure 86 Halved and Lapped Clip Joint Digital to Reality

Still, these were resolved by replicating the small-scale prototype with laser cutting and a 3Axis CNC machine using two-ply sheet material. Though the clips work well, stability requires an external structure, and unitability causes problems in the full-scale assembly.

7.2.2 Finger Joinery (Rigid Joinery):

A final prototype is being assembled. Adjustments are made to the edges during this process, and the necessary parameters are set. Once the adjustments and parameter settings are complete, the assembly works for the center and external layer begin. This means the prototype's components are assembled to create a stable structure.

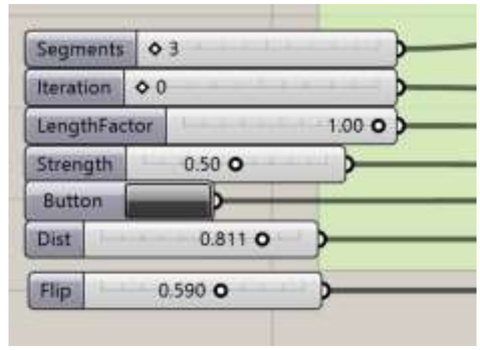


Figure 87 Adjustment for Final Permeants

The center and external layer are the most critical parts of the prototype, and attaching them will ensure that the structure is complete and functional. Overall, the statement describes the final stages of assembling a prototype, which involves careful adjustments and precise assembly to ensure a stable and available product.

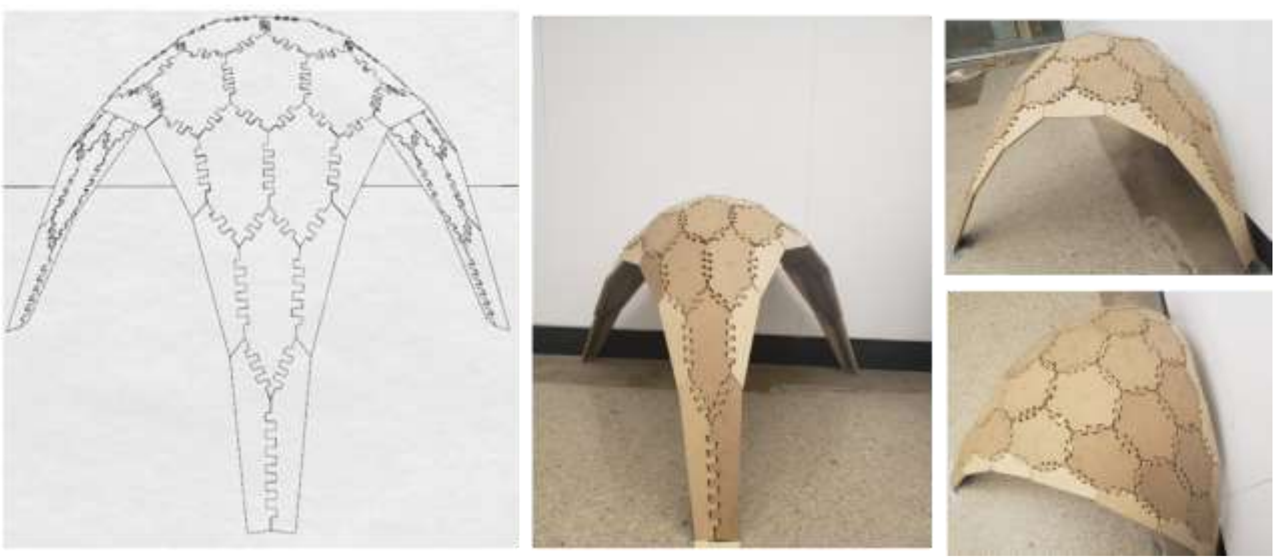


Figure 88 Finger Joinery Shell Structure

After the assembly and fabrication, the research on finger joinery, the structure's liner profile, and curvature geometry must be suitable for use with a 3-axis computer numerical control (CNC) machine. This means that the shape and contours of the structure must be compatible with the capabilities of the CNC machine to ensure accurate and precise cuts. Additionally, the curvature of the external layer of the form is crucial in ensuring that the overall structure is stable. On the other hand, for clip joinery, the clips must be designed following the curvature of the structure's geometry. This is important because the pins connect distinct parts of the structure and must be prepared to fit correctly and provide sufficient support for the overall structure. Therefore, it is possible to design the clips to be more complex to accommodate a structurally stable complex curved geometry.

Chapter 8

8.1 Conclusion:

Over the past few decades, there have been significant changes in architecture due to advancements in computational technologies. These changes have impacted the design processes, moving from traditional "design recipes" to "design optimization." In addition, improvements in computational design and fabrication technologies have revolutionized the way designers approach materials, making them a crucial element in modern architecture. This study centered on the potential of timber joinery to promote material-conscious designs and had three primary objectives:

Firstly, to investigate the role of computational design and digital fabrication technologies, particularly the 3-axis CNC machine, in creating and manufacturing intricate timber structures utilizing interlocking wood joinery as the primary connection method. Secondly, it uses parametric modeling to generate parametric wood joints that are both rigid and elastic for specific complex geometries of segmented components. Lastly, to construct a full-scale physical prototype made of wood to test the feasibility of the developed elastic clip-Tenon joint and finger joinery. The aim was to verify the applicability of these joints in real-life scenarios.

After conducting a literature review, it was discovered that advanced technologies provide an opportunity to enhance existing wood joints and create new ones that were previously impossible to design and fabricate. The research focused on creating digital prototypes and physically fabricating two kinds of joints using the most available simple machine, the 3-axis CNC machine, and laser cutting. The primary focus of the research was to create digital prototypes and physically fabricate two kinds of joints using the most available simple machine. The digital computational form finding is developed using advanced architectural software, especially the Rhino and Grasshopper scripts. The shape and structural optimization are done using architectural software, and the Finite Element Method is used to solve and observe the structural stability of the digital form using algorithms. The fabrication system using the simple 3-axis CNC machine and laser cutting will help develop complex structures with integrated wood-to-wood connections, at industrial and institutional levels, with advanced fabrication techniques. Filling the fingers and clips for the perfect fit and precision are essential to make it an ideal fit.

There are promising areas for future research concerning complex interlocking joints, including developing material systems that meet the requirements of essential building components and consider factors such as tightness, isolation, integration, and practical applications in structures like roofs and facade panels. Another area is investigating the structural performance of joints and systems and applying this information in joint and structure design. One potential place for research is to expand the investigation of elastic and rigid joints to include other joint types and to create material systems that merge wood joints with other lightweight materials. Architects and engineers who seek sustainable and innovative designs have immense potential to explore intricate structures and the corresponding methods for connecting wooden components. Relying on predetermined solutions or formulaic approaches to architecture is no longer sufficient, given the transformative influence of digital fabrication and computational design technologies on traditional materials, especially wood and wood joinery. By combining the inherent qualities of wood with innovative computational technologies, "wood joinery" provides architects with a vast array of possibilities to express the intricacies of the present era. This research strives to provide the best possible answer to the question at hand and serves as a modest contribution to the field of computational design and fabrication of timber joinery, particularly in the context of complex geometry. The future research will take it to the next level and delve into advanced aspects, particularly focusing on design and fabrication systems. This includes exploring the potential of advanced fabrication and construction techniques to scale up the application of timber construction, with a specific emphasis on sustainability advancements.

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Appendices

1 *Millipede Analysis Grasshopper Script

2 *Kambra 2d Grasshopper Script

3 * Finite Element Method Analysis Kambra 3D GH Script

4 *the Finger Joinery Grasshopper Script

5 *Halved and Lapped clipped Joinery GH Script Triangular Base

6 *Revised Halved and Lapped Joinery Script Hexagonal Segmental Base

Are Detailed Describes As Follow.

1*Millipede Analysis GH Script

2* Kambra Kambra 3D GH Script

3*Finite Element MEthod Analysis Kambra 3d Grasshopper Script

4 * Finger joinery GH Script

5*Halved and Lapped Clip Joinery Triangular Base

6 * Halved and Lapped Clip Joint GH Scrpit Hexagonal Base

Offset
Offset
Loft
Material Thickness
0.06
RSlits
Lng
Data
Center
For Each
CP
Cull i
Split
Item
Data
Srf
Srf
Lng
Lng
Series
Area
thickness
surface
Cluster
Series
Area
thickness
surface
Cluster
Wires
Swatch
Swatch
Tag
Preview
Swatch
Swatch
Swatch
Tag
Preview
Preview
Nest?
True
Cull
Cull
Planar
Planar
Spacing
0.500
Tolerance
Pack
Pack
Crv
Spacing
0.500
Crv
OpenNest
OpenNest
Z
Srf
Crv
Extr
Extr
Crv
Lng
Lng
Series
Area
Series
Area
Swatch
Swatch
Tag
Preview
Swatch
Swatch
Tag
Preview