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FABRICATION OF COMPLEX FORMS IN THE DIGITAL AGE: RE-EXPERIENCING WOOD JOINERY IN ARCHITECTURE

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DİJİTAL ÇAĞDA KARMAŞIK FORMLARIN ÜRETİMİ ÜZERİNE: AHŞABIN BİRLEŞİMLERİ MİMARİDE YENİDEN DENEYİMLENMESİ

(Yüksek Lisans Tezi)

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ÖZET

Malzeme odaklı ve geleneksel bir yöntem olarak ahşap strüktürlerin yapımında kullanılan "geçmeli ahşap birleşimler" günümüzde de sayısal yöntemlerle tasarlanmış ve üretilmiş karmaşık çerçeve ve yüzeylere sahip yapılarda ve özellikle geçici pavyonlarda sıklıkla görülmeye başlamıştır. Bu araştırma, ahşap yapılardaki geleneksel yapım pratiklerini gelişmiş teknolojilerle yeniden anlamaya ve dijital ortamda kurgulanan "zanaatkarlığın" çağdaş uygulamalarını yorumlamaya katkı sağlamak amacıyla planlamıştır. Çalışmanın amacı sayısal tasarım ve üretim teknolojilerinin ahşap geçmeli detaylarla tasarlanmış ve üretilmiş karmaşık formlu ahşap strüktürlerdeki rolünü araştırmaktır. Araştırma amaçlı tasarlanan ve üretilen "üç örnek çalışma" tezin ikinci ve üçüncü hedefleri olan karmaşık geometrili formlar için parametrik birleşim detayları tasarlamak ve geliştirilen birleşim detaylarının uygulanabilirliğini göstermek için fiziksel modellerinin üretilmesi sürecini kapsamaktadır. Çalışmanın sonucunda elde edilen parametrik "yarım kertmeli birleşim detayı" modeli, "zıvanalı geçme birleşim detayı" ile karmaşık bir kafes yapısının panellerini "sandık geçmesi" ile birleştiren T formlu elastik zıvana kenet tasarımı, parametrik tasarım araçlarının ahşap geçmeler konusundaki potansiyellerini ortaya koymuştur.

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FABRICATION OF COMPLEX FORMS IN THE DIGITAL AGE: RE-EXPERIENCING WOOD JOINERY IN ARCHITECTURE

(M. Sc. Thesis)

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ABSTRACT

Interlocking wood-to-wood joints (wood joinery) in wooden structures is a material driven and a traditional structural method that nowadays can be seen being used frequently in digitally designed and fabricated complex frame and plate wooden structures and pavilions. This research was planned so as to contribute to the understanding of advanced technologies' impact in revitalizing the use of traditional building practices in timber structures and the contemporary applications of an established craftsmanship in a digital environment. The first objective is to explore the role of computational design and digital fabrication technologies in designing and manufacturing complex wooden structures making the interlocking wood joinery as the main connection type. As a result of this inquiry, three explorative case studies were defined for the second and third objectives which are to develop parametric joints for selected complex geometries and to fabricate a physical full prototype from wood to test the applicability of the developed joints. The research resulted in developing a digital prototype for a parametric rigid “halved and lapped” and “mortise and tenon” lengthening frame joints, a digital model for a complex lattice structure with a parametric rigid finger-tenon lengthening plate joint, and a digital and full scale physical prototype of a wooden shell pavilion with a parametric elastic clip-tenon T-shaped plate joint.

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TABLE OF CONTENTS

Page

ÖZET iv

ABSTRACT v

ACKNOLEDGEMENT vi

TABLE OF CONTENTS vii

LIST OF TABLES ix

LIST OF FIGURES x

SYMBOLS AND ABBREVIATIONS xiii

1. INTRODUCTION 1

2. WOOD AND WOOD JOINERY IN ARCHITECTURE 5

2.1. Wood In Architecture 5

2.2. Emergent Complex Wood Structures in the Digital Age 8

2.3. Wood Joinery 14

2.3.1. Definition and history of wood joinery 14

2.3.2. Typology of wood joinery 16

2.3.3. Examples of wood joinery in complex structures 21

2.4. Summary 26

3. METHODOLOGY 31

3.1. Introduction 31

3.2. Research Instruments 33

3.2.1. Prototyping 33

3.2.2. Parametric modeling 35

3.3. Research Procedure 35

Page

4. CASE STUDIES 37

4.1. Case Study 1: “Parametric Halved and Lapped” and “Mortise and Tenon” Lengthening Frame Joints 37

4.2. Case Study 2: Parametric Rigid Finger-Tenon Lengthening and Cross Plate Joint for a Complex Lattice Structure 42

4.3. Case Study 3: Parametric Elastic Clip-Tenon T-Shaped Plate joint for A Wooden Shell Pavilion 45

4.3.1. Introduction 45

4.3.2. Material selection 47

4.3.3. Wood elasticity/ deflection test 48

4.3.4. Single joint options 49

4.3.5. First physical scaled prototype 52

4.3.6. Second physical scaled prototype 54

4.3.7. Parametric clip -tenon joint 56

4.3.8. Digital form finding 59

4.3.9. Plates boundary mapping, tenons and joints orientation 61

4.3.10. Tagging and nesting 63

4.3.11. Fabrication 65

4.3.12. Assembly and disassembly 67

5. CONCLUSION 71

REFERENCES 75

CURRICULUM VITAE 81

LIST OF TABLES

Table **Page**

Table 2.1. Innovative application of traditional wood building systems 10

Table 3.1. Research case studies 32

Table 3.2. Case studies' digital and physical prototypes 34

Table 4.1. Birch plywood technical characteristics 47

Table 4.2. Deflection values for plywood 48

Table 4.3. Single joint- option one 49

Table 4.4. Single joint- option two 50

Table 4.5. Single joint- option three 51

LIST OF FIGURES

Figure **Page**

Figure 2.1. (a) Log construction, (b) timber frame construction, (c) light frame construction 7

Figure 2.2. Examples of lattice structures, Metropol Parasol, Autobahn Church..... 13

Figure 2.3. Wood folded plate structures: Landesgartenschau Exhibition Hall (top left), Skilledin Office (top right), Viweing Center in Osaka (bottom left), ICD/ITKE Research Pavilion 2011 (bottom right)..... 14

Figure 2.4. Timeline of wood joinery and timber building systems in architecture..... 16

Figure 2.5. Zwerger's joint taxonomy 17

Figure 2.6. Halved and lapped joint's group (left) and tenon group (right) 17

Figure 2.7. 50 Digital wood joints 19

Figure 2.8. Clip-tenon elastic joint..... 20

Figure 2.9 Scarf and halving joints for the clubhouse's wood lattice structure, ... 22

Figure 2.10. (a)Assembling detail (b) joinery detail and (c)tamedia office building wood frame structure 22

Figure 2.11. (a) ICD/ITKE 2011 research pavilion (b) finger joint detail and (c) robotic fabrication of plates..... 23

Figure 2.12. IBOIS folded plate structure prototypes..... 24

Figure 2.13. Kobra pavillion..... 24

Figure 214. Sliding slot joints..... 25

Figure 2.15. Japanese Chidori joints..... 26

Figure 2.16. Snap-fit joint..... 26

Figure 2.17. Wood joinery classification for parametric geometry modeling purposes 28

Figure 2.18. Simplified classification of existing ınterlocking wood joinery in complex structures 28

Figure 2.19. Potential research areas in wood joinery for complex structures 29

Figure 2.20. The categories of explored joints in author's research..... 30

Figure **Page**

Figure 3.1. Research's parametric model structure 35

Figure 4.1. 2D and 3D NURBS curves 38

Figure 4.2. Up: mortise and tenon joints' control points; down: halved and lapped joints' control points 38

Figure 4.3. Grasshopper definition for mortise and tenon lengthening joint 39

Figure 4.4. Geometry processing for parametric mortise and tenon lengthening joint 39

Figure 4.5. Parametric mortise and tenon joints 40

Figure 4.6. Grasshopper definition for halved & lapped lengthening joint 41

Figure 4.7. Parametric halved and lapped joints 41

Figure 4.8. Finger-tenon lengthening and cross plate joint 42

Figure 4.9. Grasshopper definition for a lattice structure with finger-tenon lengthening and cross joints 43

Figure 4.10. Geometry processing for the lattice structure and it is finger-tenon lengthening and cross joints 43

Figure 4.11. Relief holes for joint's ınside corners 44

Figure 4.12. Complex lattice structure 44

Figure 4.13. Cantilever snap-fit joint 46

Figure 4.14. Snap-fit joint prototype by Christopher Robeller 46

Figure 4.15. Third case study procedure 47

Figure 4.16. Deflection test 48

Figure 4.17. Double curved surface from four quadratic plates 52

Figure 4.18. First physical scaled prototype: plates and joints 52

Figure 4.19. Fabricated first physical scaled prototype 53

Figure 4.20. Joints appropriate length to width ratio versus undesired length to width ratio 53

Figure 4.21. Second physical scaled prototype: plates and joints drawings 54

Figure **Page**

Figure 4.22. Fabricated second physical scaled prototype..... 54

Figure 4.23. Clip-tenon joint anatomy and parameters..... 55

Figure 4.24. Parametric clip-tenon joint Grasshopper definition..... 56

Figure 4.25. Clip-tenon joint: iterations..... 57

Figure 4.26. Range of angles covered when the distance parameter (d) value is fixed at 2.55 cm..... 58

Figure 4.27. Effect of ınner arm length on avoiding excessive deflection that might lead to ınner and outer arm cracking. 59

Figure 4.28. Kangaroo form finding definition adapted from Daniel Piker 60

Figure 4.29. Digital form finding for a full scale prototype shell with planar quad mesh, iterations ınside the frames is for shell options with fully planar quads 60

Figure 4.30. Grasshopper definition for generating untrimmed surfaces from mesh faces 61

Figure 4.31. Inward and outward joint's orientation planes..... 62

Figure 4.32. Panels boundary mapping and tenons and joints' 3d orientation 62

Figure 4.33. Full-scale prototype's top view and side view 63

Figure 4.33. Full-scale prototype's front and perspective view..... 63

Figure 4.35. Tagging and nesting Grasshopper definition..... 64

Figure 4.35. Example for the tagging engraved on top of plates and joints 64

Figure 4.37. Fabrication with laser cut 65

Resim 4.38. Consumed martials for the full scale prototype..... 66

Figure 4.39. Full-scale prototype skin and frame 67

Figure 4.40. Full-scale prototype assembly 67

Figure 4.41. Full-scale shell prototype with elastic clip-tenon joints 68

Figure 4.42. Full-scale prototype, picture from inside looking up 69

Figure 4.43. Clip-tenon elastic joint, detail for the joint mechanism..... 69

SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this study are presented below along with explanations.

Symbols	**Explanations**
cm	centimeter
m	meter
mm	millimeter

Abbreviations	**Explanations**
3D	Three Dimensional
BIM	Building Information Modeling
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CLT	Cross Laminated Timber
CNC	Computer Numerical Control
ICD/ITKE	Institute for Computational Design and Construction / Institute of Building Structures & Structural Design
NURBS	Non-Uniform Rational B-Splin

1. INTRODUCTION

The twenty-first century has witnessed on a large scale the use of digital technologies that drive a novel approach in all kinds of man-made products, including architectural ones. Today, the use of CAAD (Computer aided architectural design) in architecture has been extended from being a medium of representation to media of design and manufacturing. CAD/CAM (Computer aided design/computer aided manufacturing) and CAAD have also made a shift from exclusively designing the product to inclusively designing the process. There is no doubt that CAD/CAM applications have been rapidly changing the conventional architectural design and construction processes since the end of the last century. In this process, researchers and practitioners have been seeking new tectonics and materials which reveal the advantages of using cutting-edge technologies without sacrificing the sustainable aspect of the manufacturing process. Advances in material science, interdisciplinary studies and innovative design and fabrication technologies, as well as extremely high data crunching capacities, have resulted in changing the perspective regarding the role of building materials in the digital age, and this can be seen in the applications for different building materials in contemporary architecture.

A well-known building material that has a high potential for benefiting from the above-mentioned advancements is “wood”, which has been used as a main building material for centuries. Wood craftsmanship has developed over time tools and methodologies to cut, join and construct wooden/timber structures. The advantages of wood allow for sustainable and economic construction due to its characteristics as a strong and durable material with high performance level against heat and sound. In addition to these, advances in manufacturing and adhesives have played a significant role in the development of engineered timber products. All the previous characteristics together with increasing interest in sustainability and performance based design make wood a certain option for digital manufacturing in architecture.

Computational technologies nowadays enable the design and manufacturing of complex surface configurations that reflect the complexity of the design problem and cross the boundaries of Euclidean geometries to a more freeform topological geometry. Looking back to the beginnings of the 2000's, one sees that the use of computational technologies

for design and manufacturing in architecture has witnessed a remarkable growth; design and fabrication have become an integrated process where the constructability of a design proposal is being simulated, evaluated, and tested in the early design stages. Several tools for digitally fabricating building materials including wood had developed in parallel with the development of CAD/CAM and CAAD. Laser machines, computer numerical control machines (CNC) and robotics are some of the technologies that further stimulate the development of new methodologies for complex wood structure design and fabrication. During early design stage, the possibility to digitally run real time simulation, evaluation and design constructability testing resulted in accelerated generation and production of design.

Problem definition

While research in advanced wood architecture in recent years has been focused in more than one area, such as wooden high-rise and timber towers, massive wood construction, timber building systems and robotic fabrication, this research is specifically concerned with "wood joinery" which is an interlocking wood-to-wood connection which was a fundamental aspect of wood construction until the 19th century and was mainly used for assembling wood frame members in traditional timber frame structures. Starting in the 19th century, other means of mechanical and chemical connections, such as metal nails and plates and adhesive, replaced it. In the light of the above, this research attempts to investigate digital technologies that could be used to accommodate "Wood Joinery" as the main connection type in different wood component types, including but not limited to frame or plate/panel/board members.

Based on the literature which revealed the transformation of traditional types of wood joinery when aided by computational design and digital fabrication, the research problem is addressed by developing parametric wood joinery details and prototypes fabrication. Wood joinery covers a wide range of different shapes and applications and the case studies focused on parametrizing two groups of frame joints (the first case study), and two plate joints (the second and third case study). While the first and second case studies are new applications of parametric versions of previously existing rigid joints, the third case study is an application of a new concept: it describes the design and implementation of a wooden elastic clip-tenon joint. Apart from Robeller et al. (2014)'s study on the use of elastic

interlocking wooden joints, there is a lack of research and investigation and only little attention has been paid to the application of this category of joints in complex wooden structures compared to the literature available regarding rigid joints.

Based on the aforementioned knowledge, the main objectives of this research can be formulated a follows:

1. To identify and explore the role of computational design and digital fabrication technologies in designing and manufacturing complex wooden structures where the interlocking wood joinery is the main connection type.
2. To develop parametric rigid and elastic wood joints for selected complex geometries of frame members and plates components using parametric modeling.
3. To fabricate a physical full-scale wood prototype to test the applicability of the developed elastic clip-tenon joint.

Research questions

This research intends to investigate the following research questions:

1. What types of wood joinery can be developed employing recent computational design and digital fabrication technologies for designing and manufacturing complex wooden structures?
2. What is the way to model parametric wood joinery geometry using computational techniques?
3. Could a full-scale prototype be fabricated and assembled based on the developed parametric wood joints?

Research design

Case study research design is used to carry out the present study. The purpose of case study research design is to understand a complex issue or object and then extend experience or add strength to what is already known through previous research. The case study research method, as an empirical inquiry, investigates a contemporary phenomenon within its real-life context when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used (Yin, 1984: 23).

Three case studies have been undetaken in order to answer the research questions by developing digital and physical prototypes. The first case study is a parametric rigid "halved and lapped" and "mortise and tenon" lengthening frame joints, the second is a parametric rigid finger-tenon lengthening board joint for a complex wood lattice structure, and the third is a parametric elastic clip-tenon T-shaped plate joint for a wooden shell pavilion.

Significance of the study

This study is one of a few on wood joinery in complex wood structures in general and elastic wood joinery in specific. It is expected to fill a gap in the existing literature on the design and fabrication of parametric wood joinery. It will contribute to the understanding of how advanced technologies are revitalizing the use of traditional building practices in construction world, and of contemporary applications of an established craftsmanship in a digital environment.

Thesis structure

The thesis is structured in five chapters as follows:

1. Chapter one introduces the problem of interlocking wood joinery in complex wood structures, the research questions, and the proposed case studies.
2. Chapter two provides state of the art information of wood rule in architecture, rigid and elastic joints, the typology of frame and plate wood joinery and the existing examples of wood joinery in complex frame and plate wooden structures.
3. Chapter three explains the methodology applied to carry out the three case studies.
4. Chapter four presents in detail the procedure and results of the three case studies.
5. Chapter five concludes the work and presents potential areas for future research.

2. WOOD AND WOOD JOINERY IN ARCHITECTURE

2.1 Wood in Architecture

"The 18th century was about brick, the 19th about steel, the 20th about concrete, and the 21st century is about wood."
Australian architect Alex de Rijke

Wood has played an important role in human life throughout history. Usage of wood has evolved over the years from a natural material to a modern industrial product. Wood is the only renewable building material which is naturally grown from a biological tissue. It has been used and customized as a building material since very early times of human life. Wood fabric stores carbon dioxide for the entire service life. Manufacturing of wood products requires smaller amounts of energy and this is how timber's low embodied energy contributes to its positive effect on the environment. Wood is also a recyclable, biodegradable, lightweight, strong, and flexible material with environmental and performance benefits. Indeed, many studies, e.g. Coulson (2014), Forest Products Laboratory (1999), Jeska et al. (2014), Kolb et al. (2008), and Ott and Glasner (2013) reveal the advantages of using wood in the building industry.

Wood use as a building material has been strongly affected by the development of tools and craftsmanship over the centuries. Tools have developed from hand based to machine based, and from machine based to information based. O'Brien (2000) states that the building system started with a simple log structure that used large refined pieces of wood from trees as well as skeleton timber frame structure with smaller pieces in other geographical locations. Later on and prior to the industrial revolution, wood structure components were processed in standardized pieces and the individuality of components were replaced by identical parts (Buri & Weinand, 2011: 57). In the information age, CAD/CAM technologies eliminated fabrication constraints, and manufacturing of individual components is no longer economically challenging as it was during the industrial age (Buri & Weinand, 2011: 59).

In a general overview of the historical development of wood construction, building systems are listed under two categories. The first category covers the traditional form of timber construction systems in which log construction, timber frame construction and light frame construction systems are listed, while the second covers modern construction systems in which panel construction, frame construction and solid timber construction systems are listed. These are the major systems regardless of geographical location; however, variations in the application of these systems may occur because of the country, region, and form of construction (Kolb et al., 2008: 37).

Log construction:

Log construction is characterized by natural or manufactured logs arranged on top of each other to form a wall where the logs are joined together by shaping them to form an interlocking joint (Forest Products Laboratory, 1999: 16-6). Log constructions started to evolve with the development of tools during the early bronze and iron ages. In Europe, it is believed that bronze tools are responsible for the appearance of log construction whereas in Japan, axe, *chona and chisel* were used to produce the first joints for log construction and the first log buildings appeared around 300 BC (Zwerger, 2012: 121). Since conventional log construction consumes a considerable amount of forest wood, it was important to look for other alternative timber frame systems especially when human settlements expanded to non-forested areas (Auch-Schwelk et al., 2006: 66). Nowadays, the log construction system in its conventional characteristics can only be seen in a limited number of buildings (Kolb et al., 2008: 37).

Timber frame construction (post and beam construction):

Timber frame construction is an economical form of construction compared to log construction. Since it first originated to overcome the problems of losing forests (Zwerger, 2012: 239) and in geographies where timber was not available enough for log construction, the load carrying frame was constructed from large pieces of wood usually smaller than natural logs (Kolb et al., 2008: 53). Frame members were connected and secured by means of interlocking joints fabricated by hand such as mortise and tenon (Forest Products Laboratory, 1999: 16-6). Timber frame construction evolved in the 12th century, during the Middle Ages and until the 17th century and beyond using interlocking joinery, and

hard wood was the key in wood construction (Messler, 2011: 318). The current use of timber frame structure is limited to simple one- or two-floor buildings; it is challenging for multi-floor buildings because of cost and erection and construction problems (Kolb et al., 2008: 54). One example of multi- floor timber frame application in contemporary architecture is Tameda Office Building which is discussed in detail in section 2.3.3 under Examples of Wood Joinery in Complex Structures.

Light frame construction: balloon and platform frame construction:

Up until the early decades of the 19th century, timber frame was dominating wood building construction. The Industrial Revolution between the 18th and 19th centuries influenced the construction industry and, therefore, timber construction systems. Processing of new materials such as iron and concrete, the possibility of easily transferring construction materials and the inexpensive nails and standardized lumber all resulted in replacing traditional timber frame construction with light frame construction (Elliott & Wallas, 1977: 4, Kolb et al., 2008: 10).

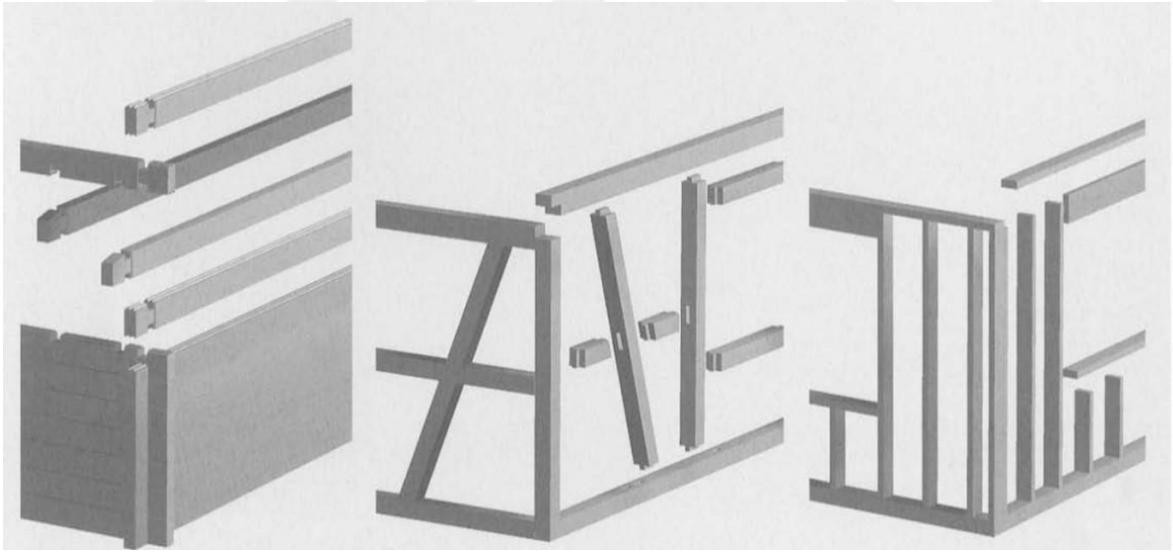


Figure 2.1. (a) log construction, (b) timber frame construction, (c) light frame construction (Kolb et al., 2008)

Panel construction:

Panel construction, which emerged during the 1980's, is considered the modern adaptation of the balloon-frame and platform-frame forms of construction; however, the elements in

it have a greater dimension than those in balloon and platform frame. It is mainly used for one and two floor houses but was also implemented in multiple floors buildings. In panel construction, the load bearing structure consists of squared sections and a protective ribs coving. The parts require accurate fabrication that is done with computer-controlled machines. Assembling panel construction relies on metal and mechanical connections fasteners. (Kolb et al., 2008: 61- 63).

Frame construction:

In modern frame construction, the load bearing structure is combined of a grid of widely spaced columns and beams with bracing supports. It is considered as the modern adaptation of traditional timber frame structure. Frame construction developed because of the newly available wood linear products, engineered building material such as glued laminated timber and connection details. Connections in frame construction can be visible connectors and fasteners and/or concealed steel components let into the timber, in addition to using interlocking wood joinery such as notched joints and mortise and tenon joints in columns and compound beams (Kolb et al., 2008: 98).

Solid timber construction:

The development of wood engineered products in panel form and on an industrial scale such as plywood has led to finding new building systems that are based on large format planer wood as a load bearing element (Buri & Weinand, 2011, Kolb et al., 2008: 111). In solid timber construction, massive wood planar components are used for building's core elements both for load transfer and enclosing purposes, and loads are carried by plate action along edges (E. Smith et al., 2015, Kolb et al., 2008: 111). Log construction is considered the old form of solid timber construction because of using solid spruce as the main load bearing elements.

2.2. Emergent Complex Wood Structures in the Digital Age

The advantages of wood as a strong, durable and renewable material in the realm of sustainable design, its availability, ease of construction and high performance, led to increase the interest in wood as an important alternative for CAM and fabrication. In fact,

realizing the potentials of wood through the use of CAAD and fabrication technologies is one of the aspects that drives the renewed interest in using wood as a structural building material (Bocanegra et al., 2014) in digital manufacturing. Wood has many advantages that bring appropriate fabrication possibilities and testing for parametric conditions, is easily cut and repaired, has wide varieties for connection types and offers a diverse range of geometric explorations (Beorkrem, 2013: 14). The fact that wood processing can be done by operating different machines adds to wood's manufacturing flexibility; laser cutters, water jets, CNC mills and routers and robotic arms are among the machines used in wood's digital fabrication.

Table 2.1 contains examples of innovative applications of traditional wood building systems via selected buildings and pavilions. The table highlights the following: (1) The innovative application of traditional wood building and fabrication systems that inspired, with the help of computational design and digital fabrication strategies, the achievement of complex freeform structures, (see examples number one, three, four, and five); (2) The development of a building system for multi-storey wood structures, (see example number two); (3) A common technique that is used in other domains such as furniture design and kerfing, and that is rephrased in parametric conditions for two wood pavilions, (see examples five and six).

Table 2.1. Innovative application of traditional wood building systems (Cabrinha, 2012, Harding et al., 2015, Keikaku-Inc., 2008, Kolb et al., 2008: 51,52,54,55, Laboratory for Timber Construction IBOIS, 2012, MATSYS Design, 2012, Achim Menges, 2010, MIT Architecture, 2012, Ramboll Computational Design, 2014, Sahu & Wang, 2015, Shigeru Ban Architects, 2013, Tamke et al., 2010, Tynkkynen, 2012, Zwerger, 2012: 93,147)

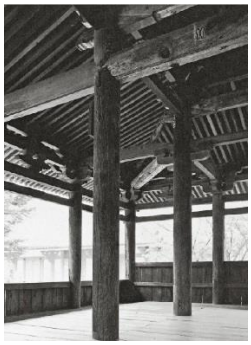
Inspiration	Analogue Transformation
 1. Log structure A traditional timber building system where horizontal logs are stacked one upon the other providing the cladding, enclosing and load-bearing functions.	 The Biomass Boiler House, 2015: For constructing the outer double curved wall from wood in its natural form 3D; scanning was used to compile a data base of selected 250 curved trees. The optimum position of each curved trunk was determined using scripting routines and pieces were matched accordingly to the structure's 3D model.
 2. Timber frame structure A load bearing framework of large structural timbers primarily connected with wood joinery such as mortise and tenon, oblique and halving joints. Structure In figure: Jodo-ji Complex,Japan.	 Tamedia New Office Building, 2013: Seven floors timber frame structure constructed using wood joinery.

Table 2.1. (Continue) Innovative application of traditional wood building systems

Inspiration	Analogue Transformation
 3. Pre-stressed timber frame gridshells Constructed from lattice with a fixed topology, which is first laid out flat and then pushed up from certain points to obtain the double curved form. Structure In figure: the Mannheim Multihalle, 1975	 (Up) Smart geometry Pavilion, 2012: A wooden gridshell assembled from straight wood members bent along geodesic lines on a relaxed freeform surface. (Down) Ongreening Pavilion, 2014: Utilizing wood's elastic behavior; the structural approach involved form-finding and bending-active plywood laths; geodesic lines originating from selected points on the surface were unrolled to form straight lines leading to an efficient 3-axis CNC fabrication.
 4. Zollinger lamella structure Type of lamella roof construction which consists of crisscrossing patterns of parallel arches of relatively short members hinged together and forming an interlocking network in a diamond pattern.	 Lamella Flock Pavilion, 2010: A freeform structure of straight beams following the principles of Zollinger lamella construction. The non-standard production was achieved through the use of heavy production techniques using glue lam, complex joints, and 5-axis milling.

Table 2.1. (Continue) Innovative application of traditional wood building systems

Inspiration	Analogue Transformation
 5. Reciprocal frame structure A structure made up of mutually supporting beams in a closed circuit.	 Dragon Sking Pavilion 2012: Up) and IBOIS modular timber structure prototype, 2012 (Down) are both examples of planer morphology of reciprocal frame structures.
 6. Wood kerfing Wood bending and twisting technique using series of cuts to direct bending and wrapping.	 (Up) Performative Wood Studio- Kerf-Based Complex Wood Systems, 2010. (Down) Kerf Pavilion, MIT Department of Architecture, 2012.

In addition to reintroducing traditional wood systems in the digital age, some new systems emerged because of the availability of new engineered timber products and advanced manufacturing. Two systems have been used and developed for more than one structure on a large and small building scale. These two systems are the timber folded plate shell and timber lattice systems for complex geometries. In timber lattice structures, a freeform surface is digitally processed to generate crossing wooden ribs to form a diagonal waffle-like pattern. The pieces are later connected with metal connectors or wood interlocking joints. Figure 2.2 shows two examples of contemporary wood lattice structures.



Figure 2.2. Examples of lattice structures, Metropol Parasol (Left), Autobahn church (Right) (Hufton+Grow, 2017; Schiffre, 2015)

Timber folded plate shell structures are types of solid timber construction, in which "assemblies of flat plates, or slabs, [are] inclined in different directions and joined along their longitudinal edges. In this way the structural system is capable of carrying loads without the need for additional supporting beams along mutual edges" (Institution of Civil Engineers, 2016). Concrete is typically used for folded plates but with the recent developments in the field of wood board products and digital fabrication have led to the construction of complex wooded folded plate structures. Figure 2.3 shows four examples of folded plate structures with complex geometry that were manufactured from wood.



Figure 2.3. Wood folded plate structures: Landesgartenschau exhibition hall (top left), Skilledin Office (top right), Viewing Center in Osaka (bottom left), ICD/ITKE Research Pavilion 2011 (bottom right) (ICD/ITKE/IIGS University of Stuttgart, 2014, Ichikawa, 2009, Institute for Computational Design, 2011a, Studio RAP, 2015)

2.3. Wood Joinery

2.3.1. Definition and history of wood joinery

In wood structures, connections can be classified into two major types: chemically (glued joints) using adhesive, or mechanically by using either dowelled joints or traditional joints referred to as wood-to-wood joints, carpentry connections or wood joinery. "Wood joinery" is the oldest among other types of connections (Jeska et al., 2014: 59). Messler (2011: 316) identified "wood joinery" as “the mating of two or more surfaces [in wood components] to form a solid unit that serves a specific function”. The specific function of structural wood joint as addressed by Mönk (1985: 77, as cited in Zwerger, 2012: 100) is to " join together pieces of timber permanently and securely in such a way that the required structural interaction of the constructional element or the construction itself is enabled". Wood joinery developed over hundreds of years of carpentry experience, from log structures with one type of joinery connecting logs edge-to-edge to a more complex timber frame structures with a multitude of joinery types for various functions. The functions of structural wood joinery as seen in both traditional and contemporary structures are: (1) to lengthen pieces in both direction (splice); (2) to make rigid corner connections (L- or T-

shaped junctions); (3) to crossover (lattice form); or (4) to connect members in oblique angle (Messler, 2011).

In the 19th century, wood joinery experienced a major shift because of the Industrial Revolution. Steam driven machines and mass production changed wood structures from timber frame structures of varied components with manually produced wood joinery that is labor intensive into balloon frame buildings of economically mass produced standardized components and metal connections (Jeska et al., 2014: 59). Manufacturers of metal fasteners provided extensive analyses and comprehensive tables of load-bearing capacity. Calculations of load bearing capacities such as tables never existed for wood joinery and, as a result, metal fasteners became easier and more manageable for assembling wood structures (Messler, 2011: 318). During the 19th century and until the 1980's, a major decline in the use of wood joinery occurred since the main building system (timber frame and log) in which these joints were part of it had already witnessed a great decline in use. The systems that evolved during this time (platform framing and later modern panel construction) were modular systems with load bearing elements mainly connected by metal connectors.

According to Jeska et al. (2014: 60), by the middle of the 1980's and with the introduction of CNC technology and integrated work flow from design to fabrication, designing and manufacturing process of joinery parts with high precision and speed became possible. By the onset of the 2000's, panel, solid and frame modern timber systems became the three main systems dominating wood building industry. In some types of modern timber frame systems, wood joinery is still used along with metal connectors.

Tamke and Thomsen (2009) state that CNC milling and later the five-axis CNC and six-axis with robotic arms milling machines allowed for mass customized fabrication of wood joinery without incurring extra costs and, thus, the efficient production of geometrical complex individualized joints that fit with little tolerances became possible. Figure 2.4. is a timeline summarizing the development of connections in timber buildings and highlighting the major turning points and transitions from one timber system to another.

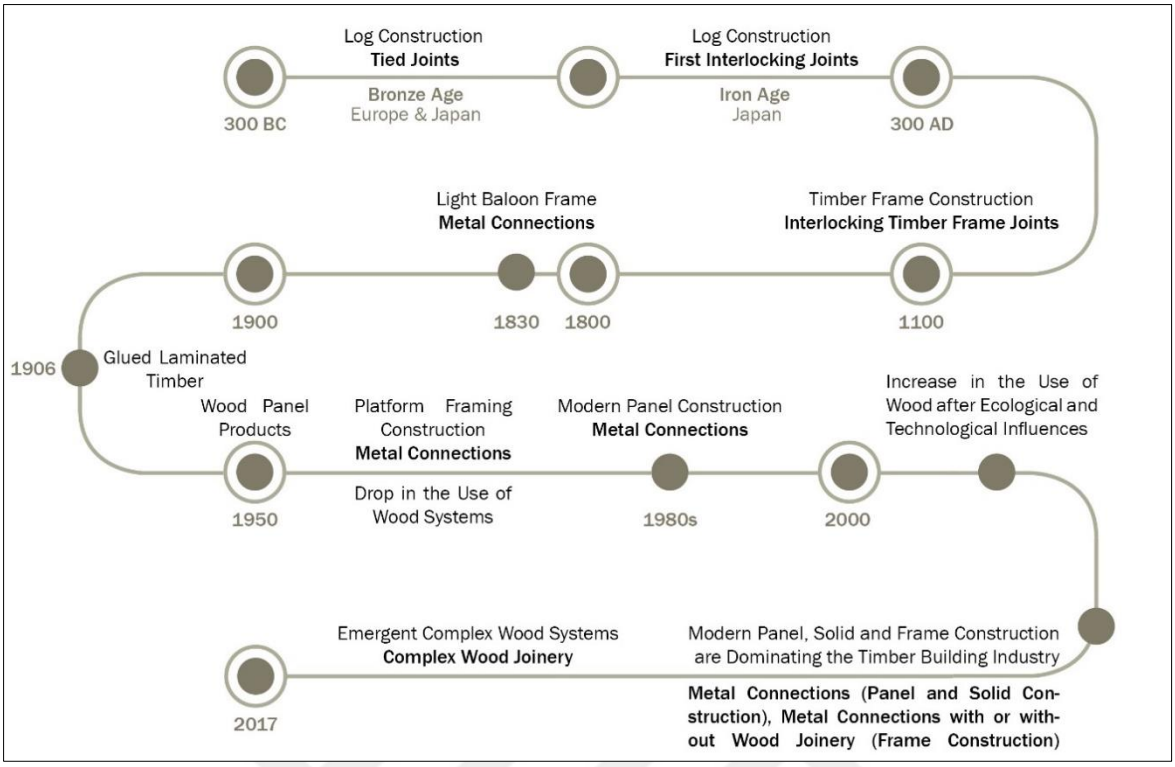


Figure 2.4. Timeline of wood joinery and timber building systems in architecture

Wood joinery is a connection produced from the material itself, i.e. wood. This results in a number of advantages in the joint structure such as having high level of prefabrication and inherited tolerance, assembly efficiency, similarity in dimensions change because of the exposure to changing temperature or moisture and the possibility to design the joint to meet specific tectonic requirements (Tamke & Thomsen, 2009). However, the American Institute of Timber (2012: 272) points out that wood joinery has limited applications in today's wood construction, as it is often restrictive or not applicable: it involves large losses of sections due to joint formation process, has complicated joinery design when used for large scale, and shows insufficient capacity to resist all types of loads.

2.3.2. Typology of Wood Joinery

Traditional wood joinery in buildings structures

Attempts to classify traditional joinery types into groups can be found in the works of Gerner (1992), Graubner (1992), Erman (1999) and many others. A seminal study in this area is the work of Zwerger (2012) who lists different families of wood joinery found in wood structures. The typology is based on two levels: the first is about the type which

describes how two pieces of wood can be joined together, and this covers the Butt joint, Notched joint, Halved and Lapped joint group, and Tenon joint group. The second level is concerned with the form of the joint; Zwerger (2012: 88-90) classified joints according to where the interlocking between two pieces of wood occurs; it could be an end grain to end grain splicing joint, an oblique joint, L-T or X open mortise and tenon, an edge to edge joint where planks of wood are joined to form larger surface, and (the last one) the L joint similar to log joints.

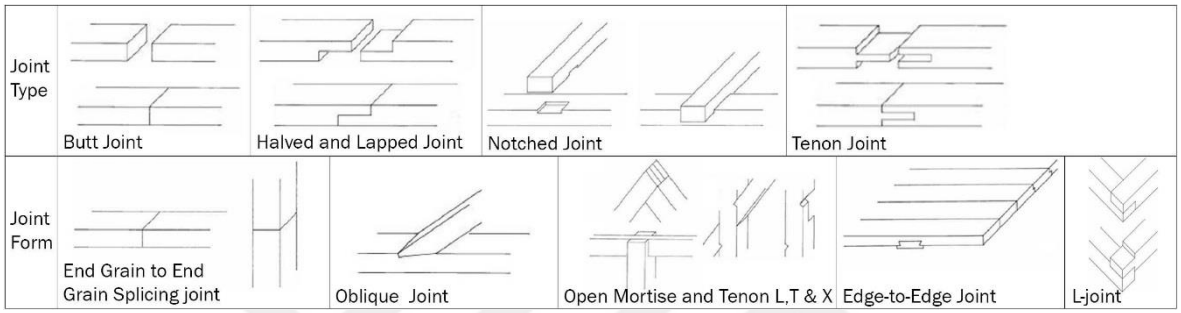


Figure 2.5. Zwerger's joint taxonomy (Zwerger, 2012: 88-90)

The two main groups of joints from which most joints are derived are the halved and lapped group and mortise and tenon group. Figure 2.6. shows these with subtypes in each group.

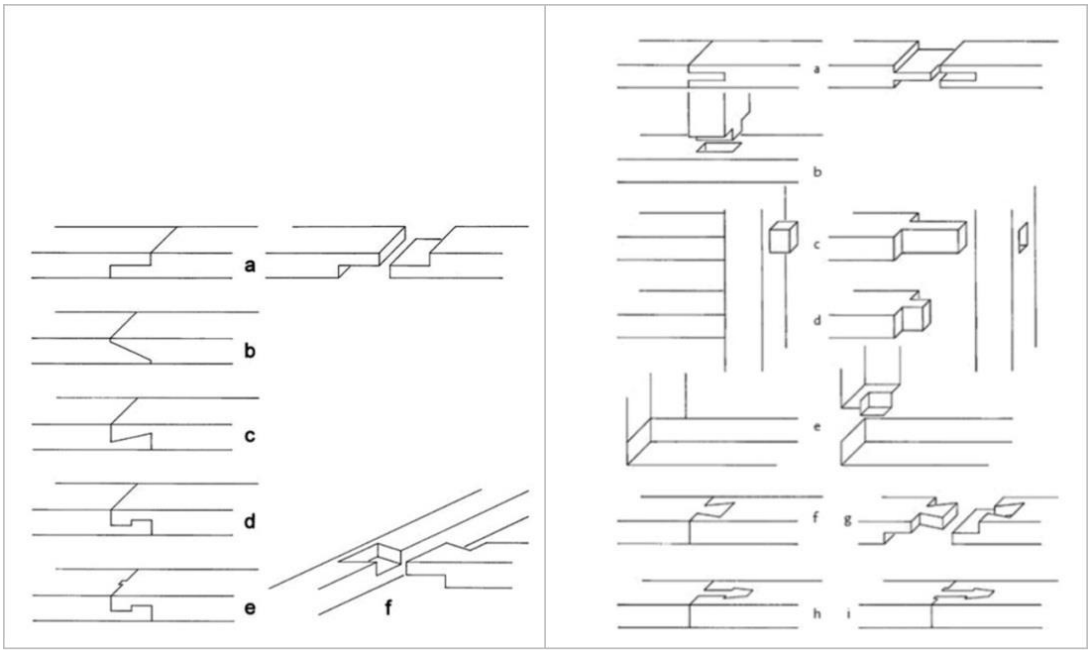


Figure 2.6. Halved and lapped joint's group (left) and tenon group (right) (Zwerger, 2012: 88-90)

Modern frame, board, and carcass ınterlocking joints

Zwerger (2012) taxonomy mostly covers joints in timber frame construction, meaning that the joints are connecting linear members. Now, with the available wood board materials, a wider groups of joints can be implemented in wood construction. One of the significant studies that cover frame and board joints is that conducted by Gros (1998) and titled "50 Digital Wood Joints". The joints are called digital because they were designed to be fabricated by computer numerical control machines. The study also provides examples of using joints; all examples are for furniture pieces. Board joints in specific have been much more experienced in furniture design than in architecture and just recently started to evolve as structural joints or as joints for building-scale components. This study is one of a few where elastic joinery is mentioned as an option among joints. The listed joints are suitable for digital fabrication and could be developed for complex geometries.

The joints are grouped under 3 categories (see figure 2.7); Frame, Board and Carcass joints. Frame and board joints are classified under several subgroups: frame joints' subgroups include lengthening, frame corner, cross and stop laps joints, and board joints' subcategories encompass lengthening , board corner , slotting , and T-shaped joints.

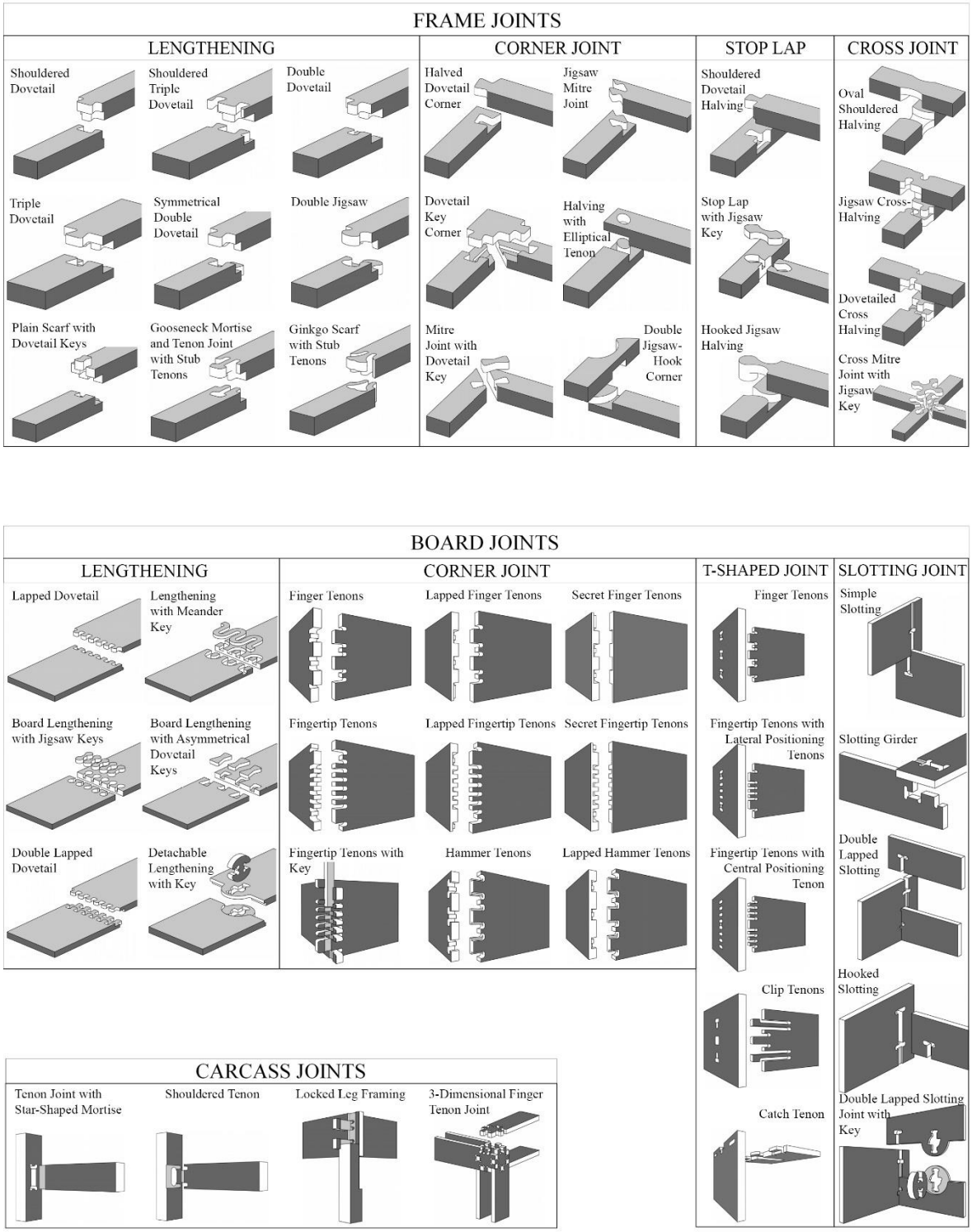


Figure 2.7. 50 Digital wood joints, adapted from (Gros, 1998)

Rigid and elastic interlocking joints

Another aspect to look at when studying joinery typology is the rigidity of the joint. Messler (2011) classifies interlocking mechanical attachments (regardless of material) into three categories: Rigid, Elastic and Plastic. To date, traditional and modern wood joinery used in building structures have all been rigid joints.

Rigid interlocks have a designed-in and pre-fabricated geometry of two opposing complementary shapes that can be joined with each other with some simple motion in some direction (Messler, 2011: 39). In elastic interlocks, one of the two opposing shapes is explicitly designed to deflect elastically and once the two parts are joined the deflected feature elastically recovers to cause interference, interlocking, and joining (Messler, 2011: 40). An example of elastic joints in wood is the Clip-Tenon T-shaped board joint (figure 2.8), one of the 50 Digital Wood Joints (Gros, 1998). Gros (1998) explains in the joint description that elastic wood joints are inspired by application of elastic joints from other fields and it is only possible now because of synthesis materials. From among wood products, plywood is the wood product that works for elastic joints.

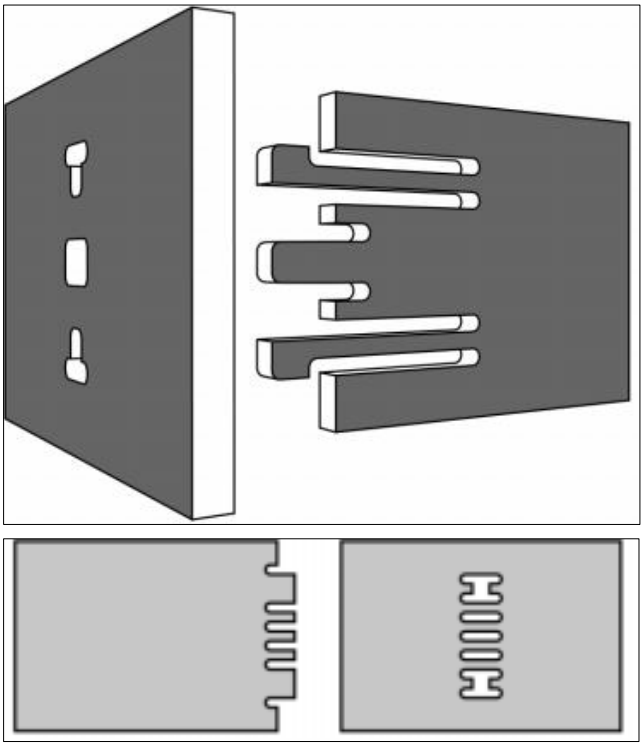


Figure 2.8 Clip-tenon elastic joint (Gros, 1998)

2.3.3. Examples of wood joinery in complex structures

The following section is designed to list some of the prominent structures that experienced a successful utilization of wood joinery as a material-driven connection type in complex structures. It should be mentioned that, for all the selected case studies, integrated design and fabrication tools were employed for the creation of joints to connect wood pieces of complex surface or frame configurations, since wood joinery is a material driven and a traditional structural method.

The majority of the examples are pavilions. The importance of pavilions to the emergence of new architectural systems, according to Reichert et al. (2014), is that " In architectural history, pavilions have served as vehicles for developing future concepts of architecture through the employment of new materials, fabrication techniques and design strategies. The architectural pavilion, with its reduced demands in regard to program and permanence, provides a suitable context for exploring construction-oriented innovation". Regarding the joint typology and due to the customized nature of most joints in the following case studies, the joint name was kept as it was referred to in the references. when it was available; renaming or matching joint type with existing typology classification was avoided.

Scarf and halving joints: clubhouse at Heasley Nine Bridges golf course

The roof structure for the threestorey building is a freeform wood lattice structure of glued laminated timber beams in single and double curvature joined with 21 tree-like columns. Roof geometry was developed as a parametric model with the help of defined data of the roof boundary. Extensive structural calculations and analysis were needed to generate the beams' complex geometries that are composed of a multitude of individual forms with different radii and changes in direction (Jeska et al., 2014: 109-116).

In this example, developed traditional scarf and halving joints were used for the first time in an engineered timber structure: the longitudinal connections between the beams are in the form of scarf joints and the connections at the intersections make use of halving joints. For fabrication, the drawings for 3500 beam segments with 476 geometries and 15000 geometrically complex halving joints pieces were automatically generated from the

parametric model; using five-axis CNC machine with new software was needed to customize fabrication. Joinery connections were strengthened with additional screw-pressure glue. (Jeska et al., 2014: 109-116).

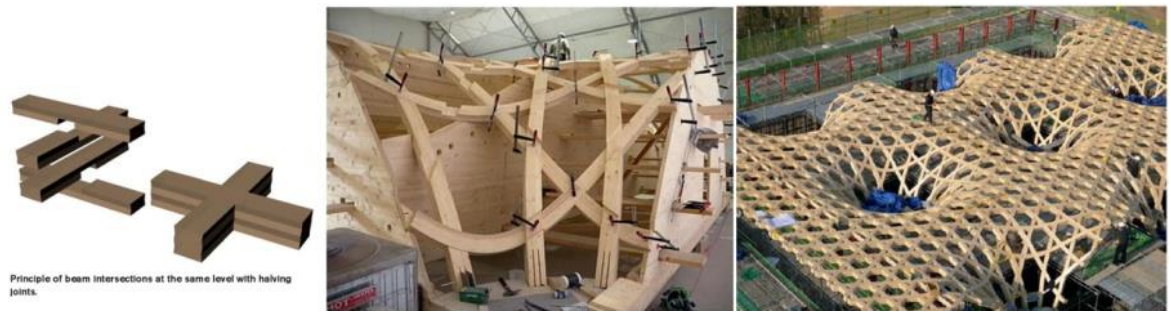


Figure 2.9. Scarf and halving joints for the clubhouse's wood lattice structure (Jeska et al., 2014)

Locking-pin joinery, Tamedia office building

Tamedia new office building is the first multi-storey building with load bearing structure and joint details made entirely from wood. The load bearing structure was inspired by Japanese wooden buildings; special dowels for wood joinery made of beech plywood connect the structure and transmit loads. The complex locking pin joint was used for three parts that form the load-bearing system: (1) the columns and beams connections; (2) the first floor truss frame; and (3) the roof's rigid frame. The design and assembling of the building required using special design tools for 3D modeling that are not commonly used in wood construction and an extremely precise CNC milling for the frame and joints from glue laminated wood (Antemann, 2014).



Figure 2.10. (a)Assembling detail (b), joinery detail, (c)Tamedia office building wood frame structure (Shigeru Ban Architects, 2013) and (4) wood joinery detail (Blumer-Lehmann AG, 2014)

Interlocking finger joints: ICD/ITKE 2011 research pavilion and Landesgartenschau exhibition hall

The designs of ICD/ITKE 2011 Research Pavilion and Landesgartenschau Exhibition Hall are based on shared principles for an innovative lightweight timber folded plate system that was developed by ICD (Institute for Computational Design) and ITKE (Institute of Building Structures and Structural Design). The biomimetic principles found in "echinoids" such as the sea urchins and sand dollars were translated into a differentiated plate structure with interlocking finger joints (Krieg et al., 2011). The plate structure is distinguished by three plate edges that always meet at just one point. This principle allows the high lightweight structure (built from 6.5 mm thin sheets of plywood) to transmit normal and shear forces (Institute for Computational Design, 2011b). Advanced computational design and simulation together with robotic fabrication made the automation of repetitive joint details in terms of design and fabrication possible (Achim Menges, 2014).



Figure 2.11. (a) ICD/ITKE 2011 research pavilion, (b) finger joint detail, (c) robotic fabrication of plates (Institute for Computational Design, 2011b) and (d) Landesgartenschau exhibition hall (Achim Menges, 2014)

Interlocking dovetail joint, IBOIS folded plate structure prototypes

In a series of studies curried out at the EPEL Laboratory for Timber Construction IBOIS, a number of folded plate structure prototypes were designed and fabricated. Robeller and Weinand (2015) proposed the use of dovetail joints for timber folded plate shell structure. No additional adhesive bonding was necessary for the assembly of the self-supported shells. Customized algorithmic tools were developed to generate the physical and virtual prototypes, the automation of repetitive custom dovetail joint geometry details and the machine code programming of the joints. RhinoPython programming interface was used for polygonal mesh processing and joints generation. The first prototype was built from 21mm Kerto-Q LVL panels and was fabricated using 5-axis CNC router, while the second

prototype was built from 77mm CLT panels and fabricated using 5-axis CNC router and KUKA KR250 robot router with an additional linear-axis table for precise 5-axis fabrication. (Robeller & Weinand, 2015: 34,55,82,94,116).



Figure 2.12. IBOIS folded plate structure prototypes: from left to right, (a) interlocking dovetail joint illustration, (b) prototype 1 folded plate shell (c), prototype 1 during assembly, (d) prototype 2 during assembly and (e) prototype 2, spanning 13.5m (Robeller & Weinand, 2015)

Spline mitred butt joint: Kobra pavilion

The design of Kobra pavilion's self-supporting shell structure (figure 2.13) is the result of performance driven penalization scheme of continuous double-curved surfaces by discrete planar meshes. After obtaining a form that allows an optimal load transfer, the numbers and positions of spline butt joints were determined through a FEM analysis. A custom Grasshopper component was implemented; it imported the results of the analysis and directly generated joint geometries. Pavilion panels were fabricated from cross-laminated timber (CLT) panels; the keys that fit the grooves in the panels were fabricated from Kerto timber material. When fabricating the joints, it was very important to line Kerto keys with the main grain direction. Wood panels and joints were cut using 5-axis CNC router and assembled with one component-polyurethane glue (Manahl et al., 2012, Shimek et al., 2012).

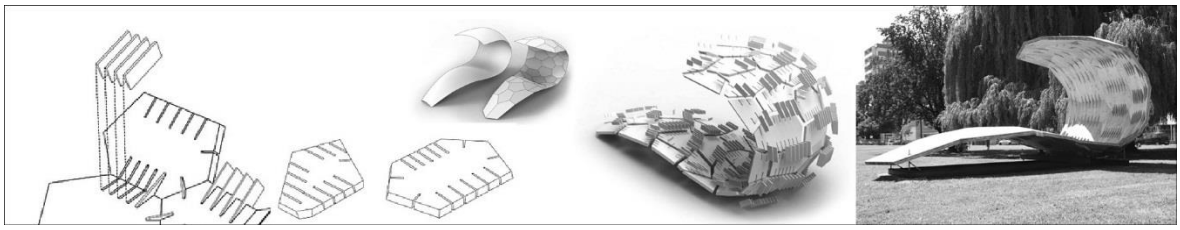


Figure 2.13. Kobra pavillion (Manahl et al., 2012)

Sliding slot joints: Dragon skin pavilion, IBOIS modular timber structure prototype and Autobahn church interior

In the Freeform Dragon Skin Pavilion, IBOIS modular timber structure prototype and Autobahn Church interior share a simple joinery detail that was proven effective to assemble these self-supporting structures. The sliding joint that connects bent wood modules in Dragon Skin Pavilion, the V-form folded modules in IBOIS prototype and the wooden ribs in Autobahn Church was achieved by cutting slots from one piece and fixing the other piece into the slot. For the three examples, algorithmic procedures generated structure and joinery detailing in addition to fabrication data including nesting and assembly (Keskisarja et al., 2012, Margaretha, 2013, Nabaei & Weinand, 2011).



Figure 2.14. Sliding slot joints: (a) sliding slot joints-Dragon skin pavilion, (b) Dragon skin pavilion (Tynkkynen, 2012), (c) IBOIS prototype (laboratory for timber construction ibois, 2012) and (d) Autobahn church (Schiffer, 2013)

Japanese Chidori joint: The Prostho museum, SunnyHills bakery building and Starbucks cafe

Architect Kengo Kuma designed several wood pavilions and buildings based on a traditional Japanese joint called Chidori. Chidori lattice is defined as "a traditional technique lacing thin rectangular wood into a lattice by making a special notch in the wood. By using this technique, a strong structure can be created without using any nails, and at the same time, it is possible to dismantle the structure at once"(Kengo Kuma and Associates, n.d.). In the three examples, Chidori joint is applied in three-dimensional space, for The Prostho Museum, Sunny Hills Bakery and Dazaifu Starbucks Cafe, it was possible for three wood members running along x, y and z axes to pass through the same point. In Prostho Museum Chidori, lattice envelop joints connected orthogonal members together, while in the SunnyHill Bakery and Starbucks Cafe buildings a parallelogram version of the Chidori was used. Although fabrication was carried out by CNC milling

machines, envelop structures were assembled manually by experienced craftsmen (Miller, 2015).



Figure 2.15. Japanese Chidori joints: (a) Chidori lattice, (b) the Prostho museum, (c) Sunny Hills bakery building and (d) Starbucks café (Miller, 2015)

Snap-fit joint: single-folded double-layer arch

The double layer arch prototype designed and fabricated by Robeller et al. (2014) is the first example of a building component that is connected with integrated elastic joints made of wood. This prototype is the first of it its kind where elastic joints are the only connection type. The snap-fit joint is applied on angled surfaces; therefore, the joint itself is from non-orthogonal faces. The fabrication of the prototype was done using 5-axis CNC machine (Robeller et al., 2014).

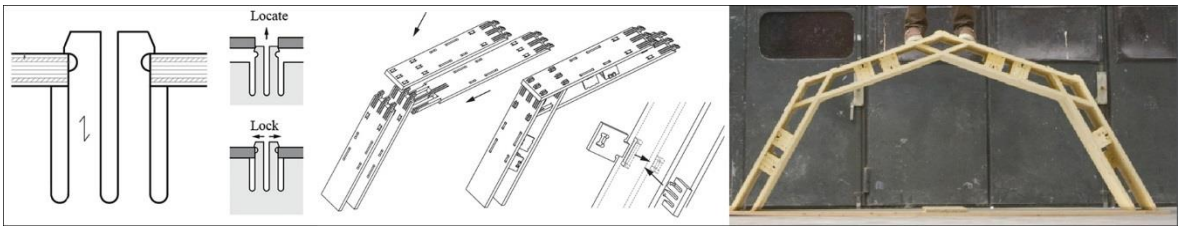


Figure 2.16. Snap-fit joint: (a) snap-fit joint, (b) assembly of the arch prototype and (c) physical prototype single-folded double-layer arch (Robeller et al., 2014)

2.4. Summary

After examining a number of recently built complex wooden structures, it sees that an integration of computational tools from design to fabrication have been achieved. The execution of these designs was not only possible as a result of the advantages of the developed computer numerically controlled machines but also thanks to the advantages of the material itself. In this respect, wood has many potentials such as being a natural, sustainable, and easy to manufacture building material.

The discussed case studies have the following general characteristics:

1. The use of new engineered timber materials of high mechanical and structural load capacity such as Kerto, CLT, post-formable grade plywood.
2. Robotic fabrication: the recent examples show increased use of robotic arms that have no fixed cutting bed, can freely move in three dimensional space and have the possibility of attaching various wood fabrication tools such as shank-type cutter and saw blade as in the fabrication of IBOIS second folded plate prototype (Robeller & Weinand, 2015: 57,58).
3. Building on the knowledge of traditional wood joinery and combining that with other form finding strategies such as biomimetic design, discretion of free-form surfaces and existing structural systems such as the folded plate system.
4. In most of the freeform structures, using wood joinery didn't lead to cancel completely, but only partially substituted, the need for other types of connections (metal or adhesive..etc). In some cases, wood joinery was the connection type for certain parts of the structure such as connecting the inner edges for each module in ICD/ITKE 2011 research pavilion, but then assembling the overall structure was done using metal fasteners.
5. The possibility to feed the computational model with important parameters derived from wood material properties such as wood bending capacity, grain direction and fabrication tool constrains.

Wood joinery classification for parametric geometry modeling purposes

As mentioned above, different ways of classifying and grouping joints exist and the number and types of joints that have been developed and used along history is countless, but for the purposes of this research that focuses on modeling the geometry of the joints parametrically, a simplified classification of frame and plate joints is shown in figure 2.17, while joints in existing complex wooden structures are shown in figutr 2.18.

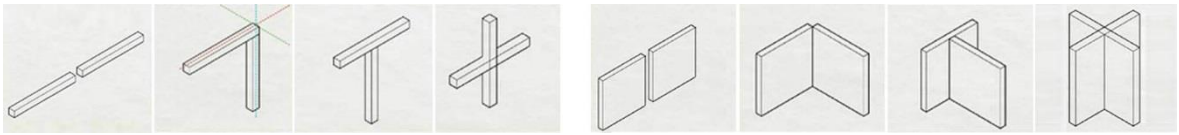


Figure 2.17. Wood joinery classification for parametric geometry modeling purposes, from left to right: (1) frame joints, lengthening, corner, t-joint and cross joint. (2) plate joints; lengthening, corner, t-joint and cross joint

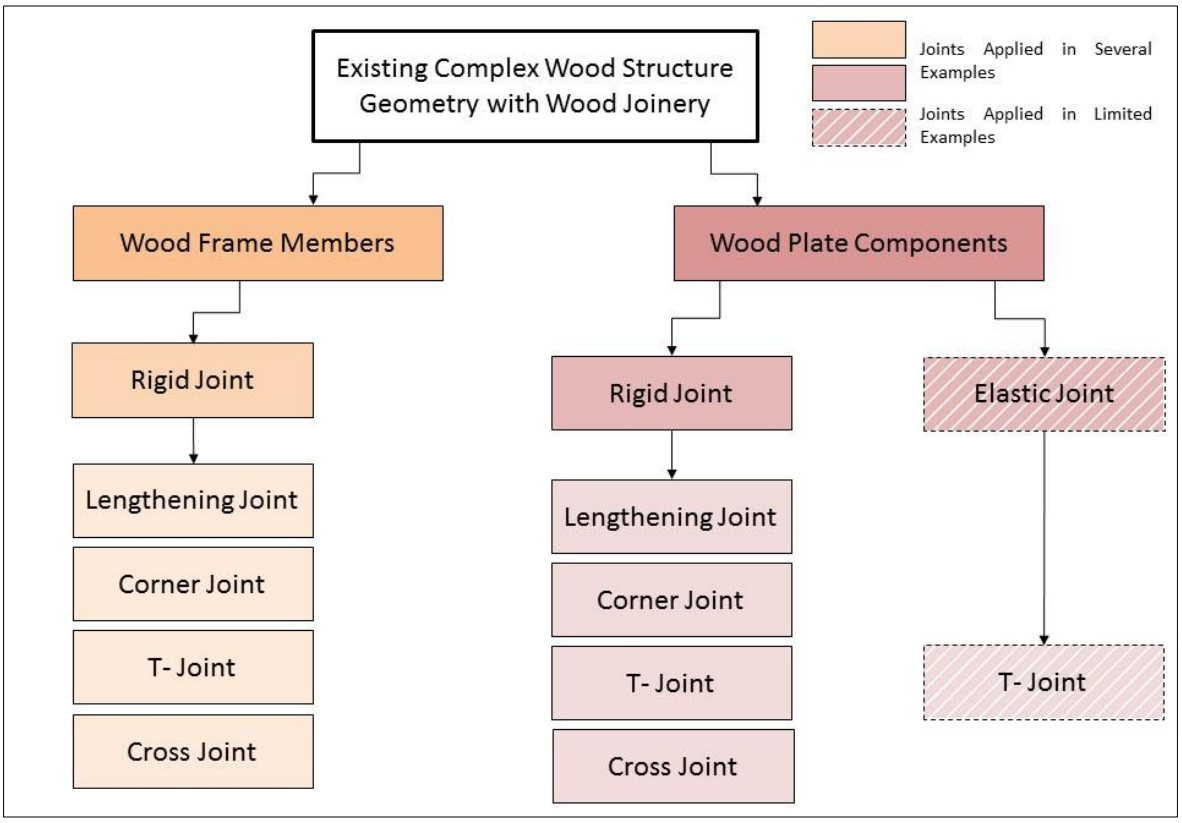


Figure 2.18. Simplified classification of existing interlocking wood joinery in complex structures

From this simplified classification, the areas of potential exploration are highlighted in figure 2.19 regardless of joint's sub-type (halved, lapped, finer, mortise and tenon…etc). In terms of rigidity degree, elastic wood joints represent a promising field of exploration that has not been studied enough or tested in the literature.

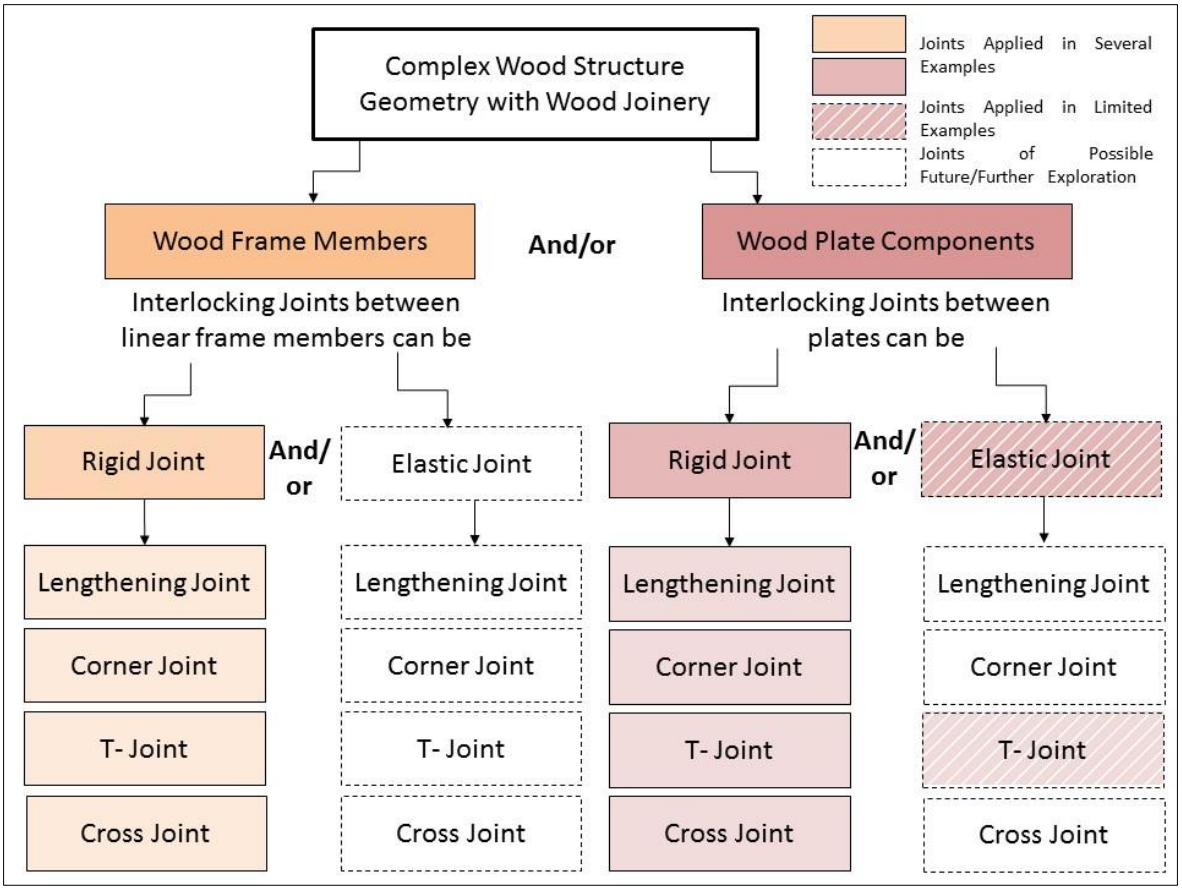


Figure 2.19. Potential research areas in wood joinery for complex structures

This research is focused on the parametric geometry and material of joints; out of the above group of joints, three areas were explored as explained in detail in Chapters 3 and 4. The categories under which the explored joints are located are highlighted in figure 2.20.

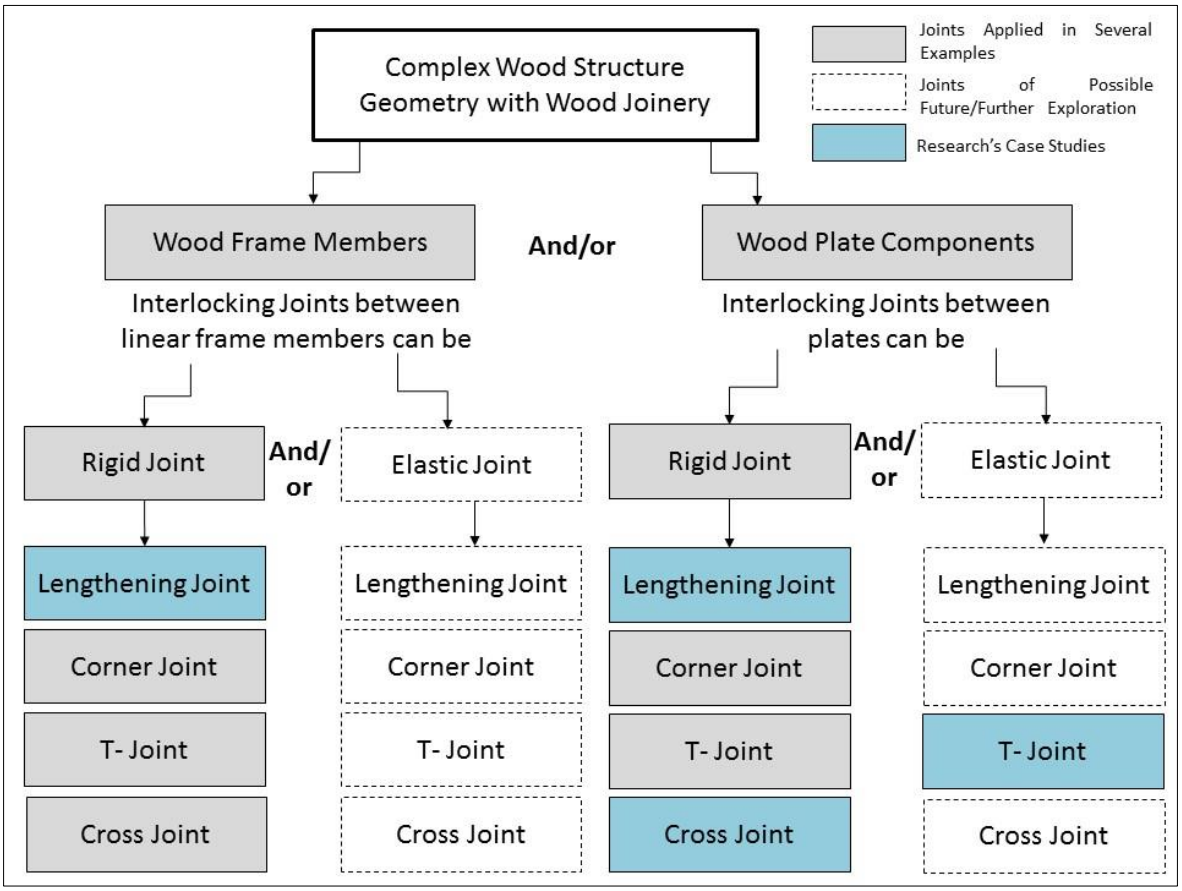


Figure 2.20. Categories of explored joints in author's research

In the following chapter, the research method applied to explore and study the three mentioned joints is explained.

3. METHODOLOGY

3.1. Introduction

Case study research design is used to conduct this study. The purpose of case study research design is to understand a complex issue or object and extend experience or add strength to what is already known through previous research. The case study research method is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, when the boundaries between phenomenon and context are not clearly evident; in it multiple sources of evidence are used (Yin, 1984: 23).

The key questions that are addressed in this research are:

1. What types of wood joinery can be developed while employing the computational design and digital fabrication technologies for designing and manufacturing complex wooden structures?
2. What is the way to model parametric wood joinery geometry using computational techniques?
3. Could a full-scale prototype be fabricated and assembled based on the developed parametric wood joints?

Three case studies were conducted to answer the research questions. The first is developing a parametric rigid "halved and lapped" and "mortise and tenon" lengthening frame joints, while the second is a parametric rigid finger-tenon lengthening plate joint for a complex lattice structure. The third is a parametric elastic clip-tenon T-shaped plate joint for a wooden shell pavilion. These joints have been purposefully selected for the following reasons:

1- First case study (Rigid "halved and lapped" and "mortise and tenon" joints): Out of the various frame and plate joints used and developed to date and implemented on a building-scale or a product-scale level, these two groups of joints are the main joint groups found in traditional timber structures. They form the basic understanding of interlocking joints functions and behavior on a building-scale level. Thus, studying and developing parametric joints based on them is an extension for a decades-long established knowledge in interlocking structural joints.

2- Second case study (Parametric rigid finger-tenon lengthening and cross plate joint for a complex lattice structure): The reason for selecting this joint to be parametrized was derived from the nature of the structure's geometry and function. Finger joints are among the most commonly tested joints in the design and fabrication of emergent complex wooden structures as seen in the examples section in this thesis. Considering this joint for assembling a lattice structure builds on previous knowledge and extends the application of this joint to another emergent structure, which is the waffle/ lattice structure.
3- Third case study (Parametric elastic clip-tenon t-shaped plate joint for a wooden shell pavilion):Following the literature review that was carried out, it was found that up until now the focus of almost all applications of interlocking wood joints were on rigid joints. Elastic wood joints were only found in one example. Selecting elastic wood joints for the third case study and as the main focus of this research aims to contribute further to the research of elastic wood joints. Table 3.1. lists the three studies that were carried out for this research and summarizes the properties covered for each joint:

Table 3.1. Research case studies

	Joint Type	Joint's Relation to Structure's Components	Rigidity Degree	Component's Geometry
1. Parametric rigid halved and lapped" and "mortise and tenon" lengthening frame joints	Halved and Lapped	Integrated	Rigid	Frame
2. Parametric rigid finger-tenon lengthening plate joint for a complex lattice structure	Finger Tenon Joint	Integrated	Rigid	Plate
3. Parametric elastic clip-tenon T-shaped plate joint for a wooden shell pavilion	Clip and Tenon	Separable	Elastic	Plate

3.2. Research Instruments

3.2.1. Prototyping

Prototype is defined as “an original model on which something is patterned” or “a first full-scale and usually functional form of a new type or design of a construction” (Merriam-Webster Dictionary 2011). Prototyping in architecture is a common instrument that seeks to explore emergent structural and material systems (Thomsen & Tamke, 2016: 50). Several authors point out the relationship between prototype and computational design in architecture. For example, In Kolarevic (2008: 157), Matthias Kohler emphasizes the importance of prototyping specifically when it comes to working with complex geometry. To Kohler, producing physical prototypes and models of the digital projects allows for the testing of construction logic and gaining a profound understanding of the spaces and their qualities. Thomsen and Tamke (2016: 52), on the other hand, identify the key aspects of adopting prototyping as a research instrument in their digital architecture research as shown in the following:

1. To test, verify and create designs.
2. To gather empirical data to inform and calibrate simulations.
3. To examine connections and detailing and at the same time understand their structural performance.
4. To test mass customization and map file to factory systems.
5. To check assembly systems and sequences.
6. To test, evaluate and communicate overall structural and material performance and scope of a particular investigation.

Physical prototypes gain a valuable importance when the research is related to materials; in order to explain the material’s performance, full scale prototypes are required, since scale models are incapable of representing the behavior of the intended system (Thomsen & Tamke, 2016: 52). Prototypes in computational design research are not limited to physical ones only, as architecture is distinguished by being the result of digital and physical interaction (Thomsen & Tamke, 2016: 52). Prototypes can be material , conceptual or digital prototypes (F. Ö. Akipek & Koziköğlu, 2007). The prototype instruments for the three case studies are classified into physical prototypes and digital prototypes.

Physical or material prototype is defined as a 1:1 scale prototype that aims to test the spatial characteristics and tectonic issues of an architectural system in terms of the relations among the factors of geometry, structure and material organization and also the coherence in between the parts and the whole constituting the architectural system (F. Akipek, 2011). Physical prototypes can be pavilions, installations, or demonstrations (Thomsen & Tamke, 2016: 50). Digital Prototype is "a parametric computational model constructed in a coded media, keeping the material and conceptual data inert interrelational within its digital components." (F. Ö. Akipek & Koziköğlu, 2007). The digital model that serves as a digital prototype is a data model that simulates generating different alternatives (F. Akipek, 2011).

In this research, physical and digital prototypes were used at different stages and for different purposes. Table 3.2 lists the prototypes for each case study. Detailed information can be found in Chapter Four: Case Studies.

Table 3.2. Case studies' digital and physical prototypes

	Digital Prototype	Physical Prototype
1. Parametric rigid "halved and lapped" and "mortise and tenon" lengthening frame joints	Two Parametric definitions for rigid "halved and lapped" and "mortise and tenon" lengthening frame joints.	N/A
2. Parametric rigid finger-tenon lengthening plate joint for a complex lattice structure	Parametric definition integrates joint and structure's geometry	N/A
3. parametric elastic clip-tenon T-shaped plate joint for a wooden shell pavilion	Elastic clip-tenon joint's parametric definition	6 alternatives of clip-tenon joints (to gather empirical data to inform simulations)
	Parametric definition for a digital form found shell	2 prototypes of 4-face double curve surface connected with elastic joints (to gather empirical data to inform simulations)
	Parametric definition for extracting fabrication and assembly data	1:1 full-scale pavilion (proof of concept)

3.3.2. Parametric Modeling

A parametric model is defined as a "set of equations that express a geometric model as explicit functions of a number of parameters" (Davis, 2013). In his book, *Elements of arametric Modeling*, Woodbury (2010) states that parametric modeling is about change, and that "parametric modelling introduces fundamental change: 'marks', that is, parts of the design, relate and change together in a coordinated way" Woodbury (2010: 11). The intent for using parametric modeling in this research is to generate joinery geometry for a structure of complex differentiated geometry and to automate the generation of details and fabrication data. The visual programming plug-in Grasshopper® was used, which is a graphical algorithm editor tightly integrated with Rhino's 3-D modeling tools ("About Grasshopper,"). Another plug-in (within Grasshopper environment) was used for digital form finding; "Kangaroo", a live physics engine for interactive simulation, form-finding, optimization and constraint solving, was used for the design and optimization of a double curve shell in the third case study.

Figure 3.1 presents the general outline and structure of the parametric modeling that is used to generate the design and extract geometric and fabrication information from the digital design process.

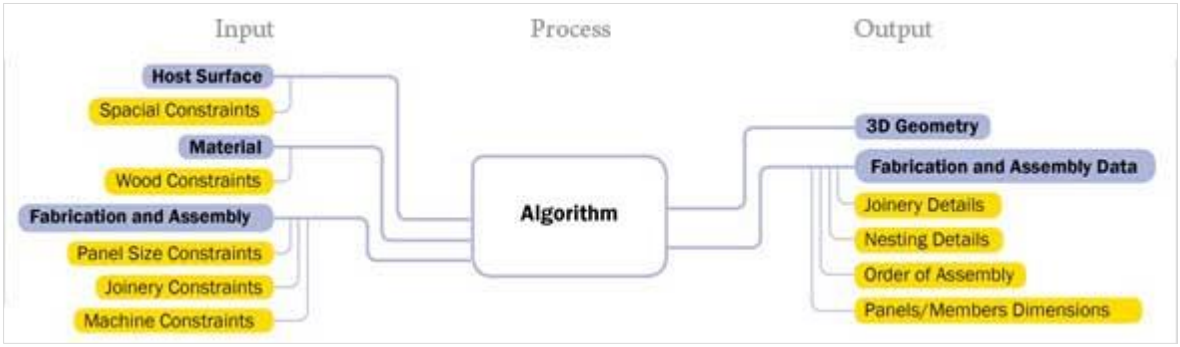


Figure 3.1. Research's parametric model structure

3.3. Research Procedure

The study was conducted in two phases:

First, a literature review was conducted to define the research problem, to understand the importance of wood and wood joinery in architecture and the typology of wood joinery,

and to highlight the applications and studies of wood joinery in contemporary complex wood structures. The result of this part was figuring out the potential investigations in wood joinery geometry research that can be further explored.

Second, three case joints were selected, one per each case study, for further investigating the possibility to create parametric versions of these joints and to utilize them for installations/structures with a complex geometry. The general procedure for the three case studies can be summarized as in the following:

1. Producing joint prototypes (digital, physical or both): Parametrizing the joint using Grasshopper, and fabricating a physical prototype for testing (if necessary).
2. Modeling a parametric host/base complex geometry using Grasshopper.
3. Using the joint's digital prototype to solve the connection details of host/base geometry and produce the detailed structure's digital prototype.
4. Fabricating a scaled physical prototype to evaluate the result of step 3 (if necessary).
5. Updating the structure's model based on feedback from step 4.
6. Fabricating a full scale physical prototype (applies for the 3rd case study only).

Chapter 4 includes a detailed description of the procedure and results for each case study individually.

4. CASE STUDIES

In this chapter, the three case studies are described in details covering both the procedure and results.

4.1. Case Study 1: Parametric Rigid “Halved And Lapped” and “Mortise and Tenon” Lengthening Frame Joints

The purpose of the first case study is to develop a grasshopper definition that can be used to generate 8 different lengthening frame joints for linear wood members of various geometries, such as straight lines, archs and non-uniform rational B-Spline (NURBS) curves of second and third degrees. As seen in the previous examples, the design and fabrication of complex wood structures often requires processing and/or tessellation of non-standard or non-Euclidean geometries into a fabricable geometry like the one found in generating planer plates from a double curved surface or generating a network of frames to represent a NURBS surface. The importance of lengthening joints for frame members of non-standard geometry and especially NURBS curves lies in making these members fabricable from multiple smaller members that can be milled or cut by CNC milling machines with the minimal waste possible.

Through the history of timber frame construction, lengthening joints were used when the length required for a beam or a column was longer than natural wood length obtained from a tree trunk. Lengthening joints are described in Zwerger (2012) study as end-grain to end-grain spliced joints. These joints can be found in both the “halved and lapped” group and in the “mortise and tenon” group mentioned before in page 17. From each group four joints were selected to create a 3 dimensional parametric joint for each of them. For parameterising the joints, they are defined based on the number of control points that make out the joint geometry (figure 4.2). By using the grasshopper definition for this case study, it is possible to generate the different joints geometry for 2D and 3D second and third degree NURBS curves (figure 4.1) by changing the number and location of control points, thus making it possible to create different options by changing few parameters.

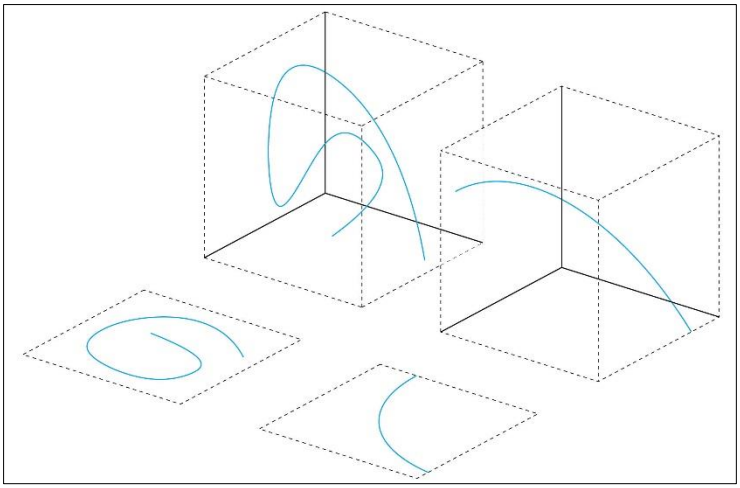


Figure 4.1. 2D and 3D NURBS curves

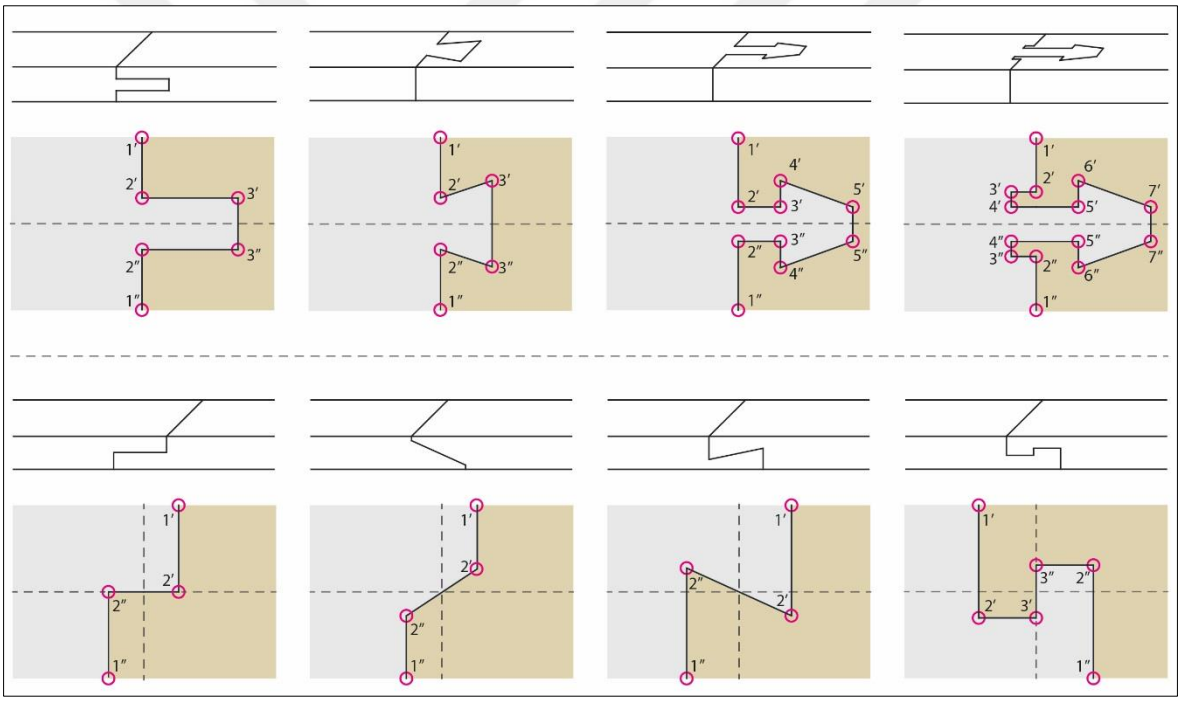


Figure 4.2. Up: mortise and tenon joints' control points; down: halved and lapped joints' control points

Two grasshopper definitions were developed: one for the mortise and tenon joints group (figure 4.3) and another for halved and lapped joints group (figure 4.6). The sequence of the parametric modeling procedure within grasshopper for the two groups of joints is the same. The only difference between the two definitions is how the control points are ordered. Figure 4.4 shows the steps for creating the parametric joints in mortise and tenon group. The only required geometric inputs are the center line of the frame member and a curve for generating the frame's profile. The profile could be of any number of sides and is

not limited to 4 sides. The other important parameters are the position of joint's control points, the number of desired parts and the fillet radius for sharp joint corners.

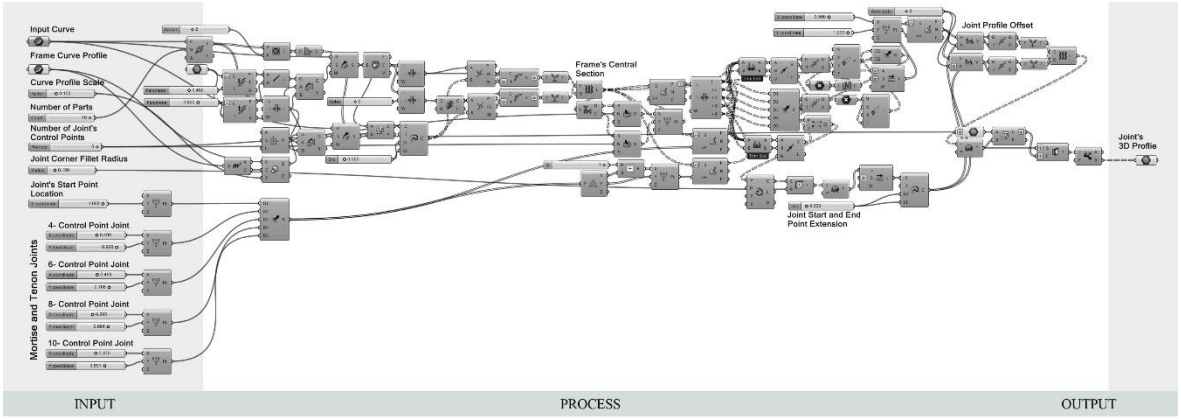


Figure 4.3. Grasshopper definition for mortise and tenon lengthening joint

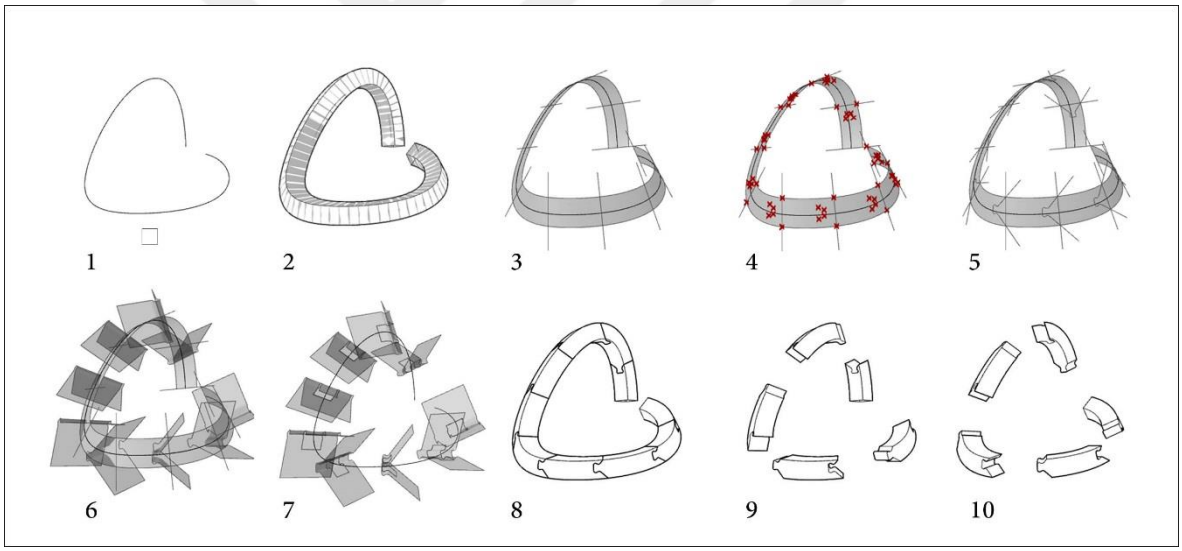


Figure 4.4. Geometry processing for parametric mortise and tenon lengthening joint

The process in figure 4.4 starts by using the frame's center curve and profile section (1) to generate the frames 3D geometry as a boundary representation (brep) (2), and at the same time a NURBS surface that splits the 3D geometry into two halves is created (3). This surface is then divided into the desired number of sub-surfaces which is 10 in this case (4). Joint's control points are then projected on each sub-surface (4) and a polyline type curve that connects them is drawn (5). After that, a lofted surface of the joint's profile is produced (6). The output of the parametric definition is 9 joint profiles (7) that are baked into geometries inside Rhino (8) and used to intersect with the 3D frame geometry

previously created in step 2 to slice it into 10 pieces (8). The last two steps (9 and 10) are joining each part of the 10 sliced geometries with the profile of the joints at the end. It wasn't possible to have this step as part of the parametric sequence and was carried out using Rhino's Boolean operation commands. Figure 4.5 shows four different mortise and tenon joints created using the developed Grasshopper definition.

Although the joints remained as digital prototypes and were not fabricated, but fabrication constraints were considered while developing the definition. For such joints with double curvature, milling the edges requires having rounded corners and having the flexibility to change the radius according to milling machine tool head's diameter, as illustrated in the four joints in figure 4.5. The ability to create rounded corners was considered in the design.

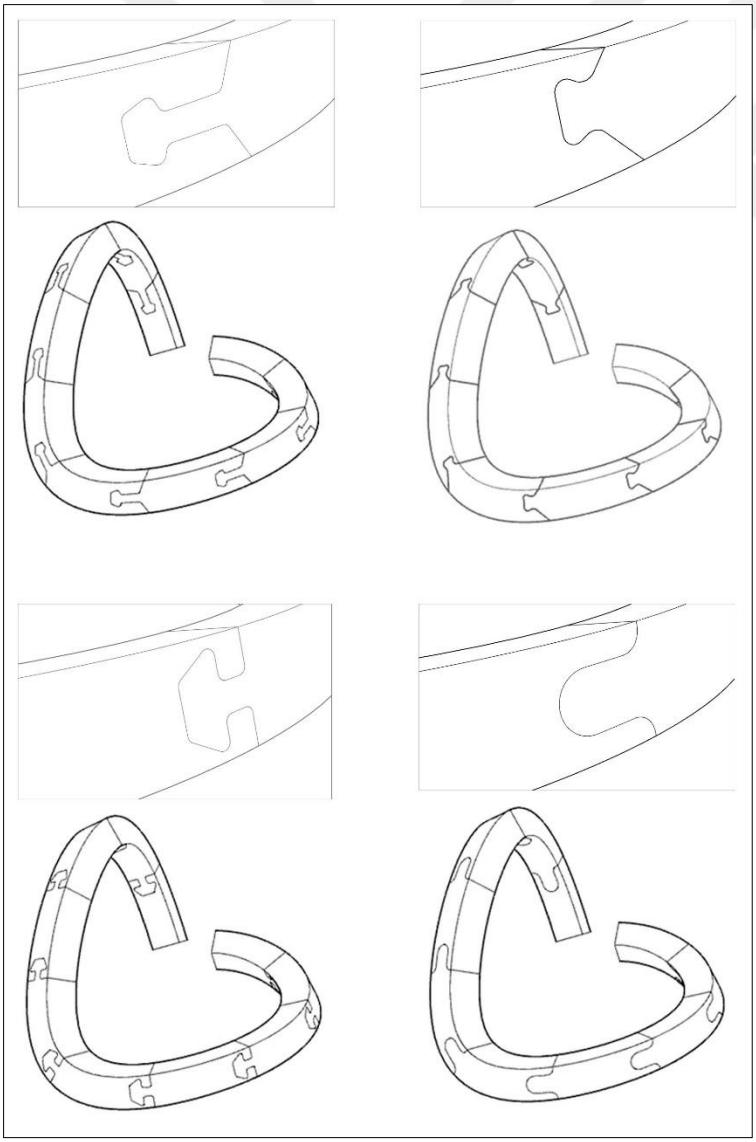


Figure 4.5.Parametric mortise and tenon joints

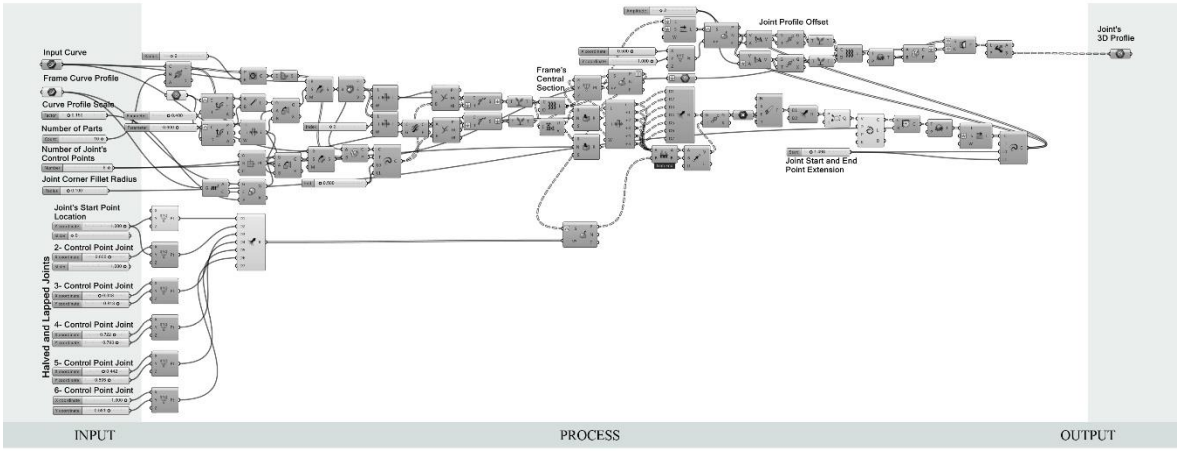


Figure 4.6. Grasshopper definition for halved and lapped lengthening joint

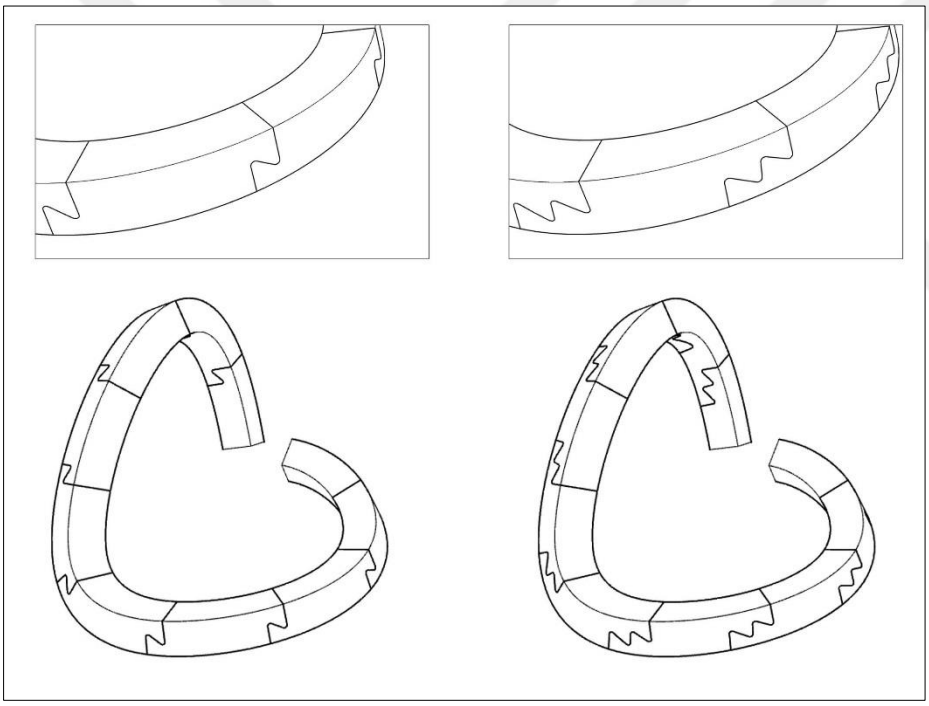


Figure 4.7. Parametric halved and lapped joints

4.2. Case Study 2: Parametric Rigid Finger-Tenon Lengthening and Cross Plate Joint for a Complex Lattice Structure

The aim of this case study is parametrizing hybrid finger- tenon joint for a lengthening and cross board joint for a complex lattice structure. Lattice structures are one of the emergent complex wood structures that have become popular recently. As mentioned in Chapter Two, interlocking slotting joints or steel connections were mostly used to connect the two groups of perpendicular boards together. This case study presents a proposal for producing the same structure but with using finger joints as lengthening joints and mortise and tenon as cross joints; these two combined together make the main interlocking connections for the structure as illustrated in figure 4.8.

Figure 4.9 shows the input, process and output in the developed grasshopper definition for generating the geometry and joints of the structure. The structure's base surface is a double curved one; it was first rationalized into two groups of crossing ribs. The structure's parameters include number, width and angle of ribs in each group, and thickness of material, while joint's parameters include the number of fingers. Figure 4.10 shows the geometry processing of the structure and the joints. It starts by lofting three curves to produce a double curved surface; after that, the center lines of the ribs are projected on the surface and a 3D ribs geometry with ribs thicknesses is generated. The first group of ribs is used to split the second group into sub-plates; for each sub-plate of the second group's ribs interlocking fingers are generated from both sides. The fingers are then used to intersect back with the first group of ribs to generate tenons (see figure 4.8 and figure 4.10).

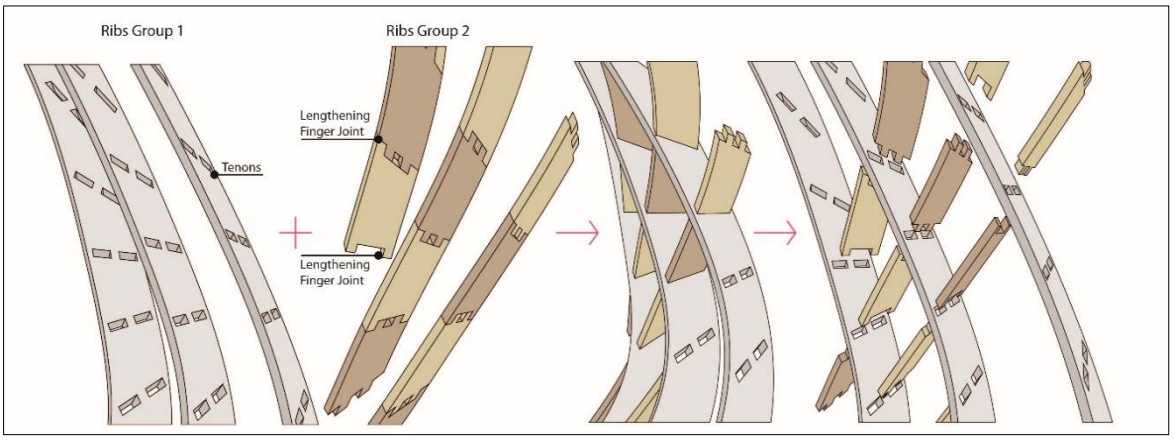


Figure 4.8. Finger-tenon lengthening and cross plate joint

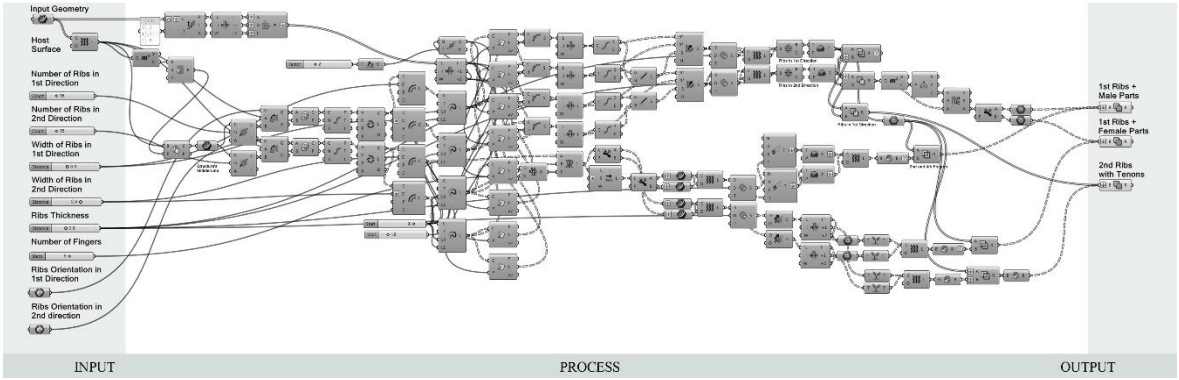


Figure 4.9. Grasshopper definition for a lattice structure with finger-tenon lengthening and cross joints

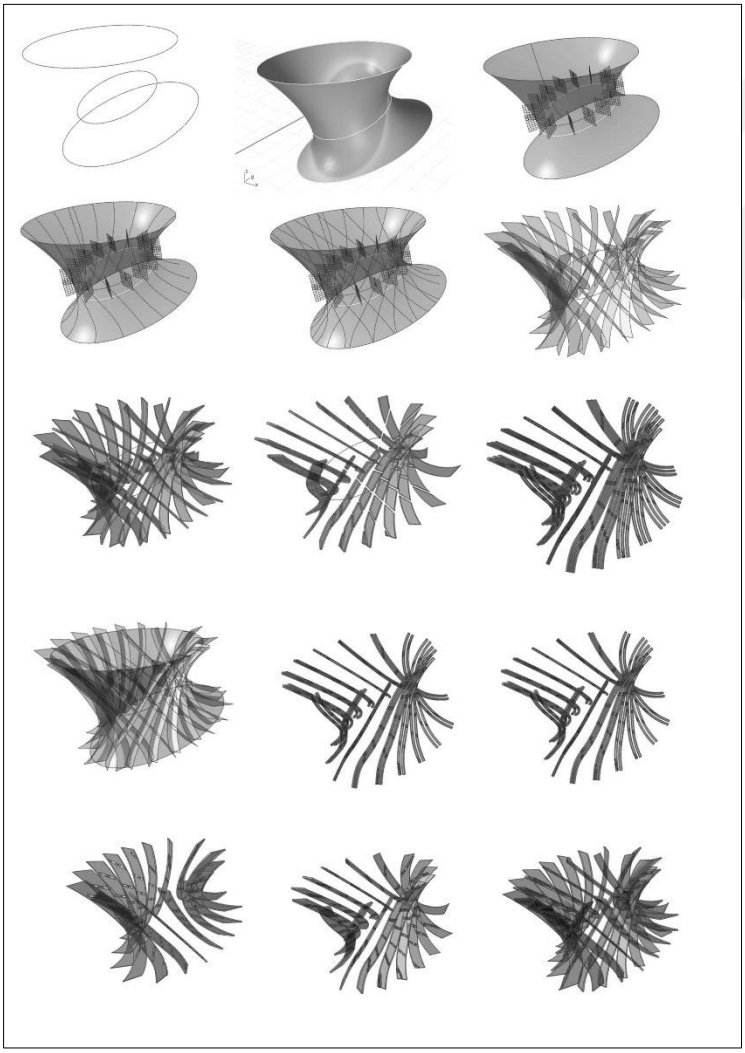


Figure 4.10. Geometry processing for the lattice structure it is finger-tenon lengthening and cross joints

This digital prototype can be fabricated with 5-axis CNC machine because the geometry of the joint features a crossing behavior and has angles in various values. The inner sharp corners need to be treated differently in order to accommodate the roundness of the machine's head as shown in figure 4.11. Instead of filleted corners, relief holes are suggested to be drilled first and then the corner is to be milled.

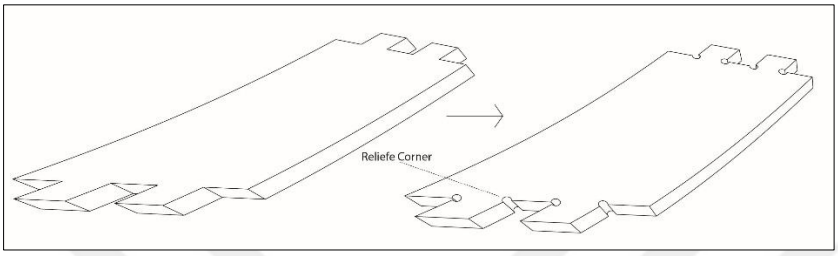


Figure 4.11. Relief holes for joint's inside corners

The overall lattice structure design is shown in figure 4.12: after assembling the parts, the joints will be all hidden and only the outer geometry of the ribs will be visible.

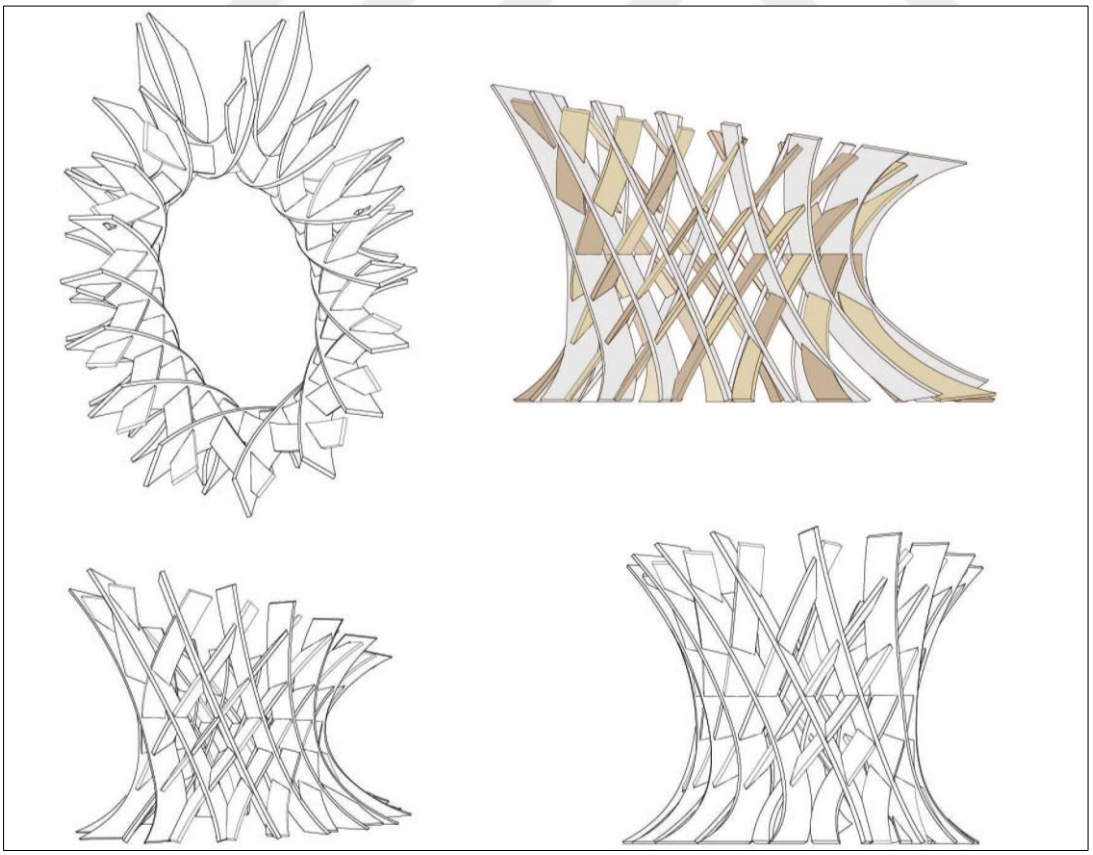


Figure 4.12. Complex lattice structure, top (up left), side elevation (up right), perspective (down left) and front elevation (down right)

4.3. Case Study 3: Parametric Elastic Clip-Tenon T-Shaped Plate Joint For a Wooden Shell Pavilion

4.3.1. Introduction

The purpose of the third case study is to develop a physical prototype for a form found shell with elastic interlocking joint as the main connection for the shell's plates. As mentioned in Chapter Two, in elastic interlocks, one of the two opposing shapes is explicitly designed to deflect elastically, and once the two parts are joined, the deflected feature elastically recovers to cause interference, interlocking, and joining (Messler, 2011: 40).

The principle in clip-tenon joint is that "a protruding part of one component, e.g., a hook, stud or bead is deflected briefly during the joining operation and catches in a depression (undercut) in the mating component, After the joining operation, the snap-fit features should return to a stress-free condition" (Buyer Material Science, n.a.: 3), thus allowing for the assembly and disassembly of the parts for endless times. (see figure 4.13)

Snap-fit joints are usually found in plastic materials; wood as a natural material with grain direction doesn't work for this type of joint but plywood materials have created the potential of elastic joint use in wood structures. Until now, examples of using elastic joints in wood structures in general and in complex structures in specific are very limited. The single-folded double-layer arch (figure 4.14) by Robeller et al. (2014), mentioned in chapter 2, is the first study on a snap-fit connection for structural wood panels (Robeller et al., 2014: 129) . Elastic joint was also listed by Gros (1998) as one of the 50 digital joints. Gros (1998) identified one elastic joint under the name Clip-Tenon joint as a detachable joint that utilizes the springiness of multiplex plywood. the joint already exists in other industries and is easy to manufacture. While researching elastic joinery for complex wood structure, one cannot think of elastic joint without thinking of engineered wood products that have made considering this joint possible.

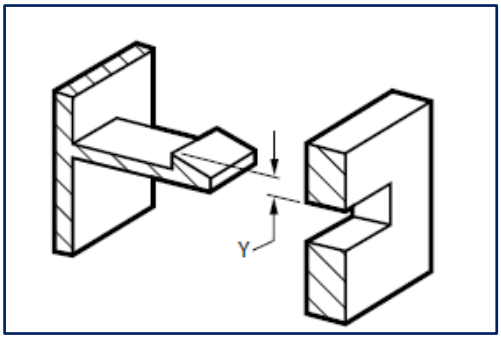


Figure 4.13. Cantilever snap-fit joint (Buyer Material Science, n.a.)

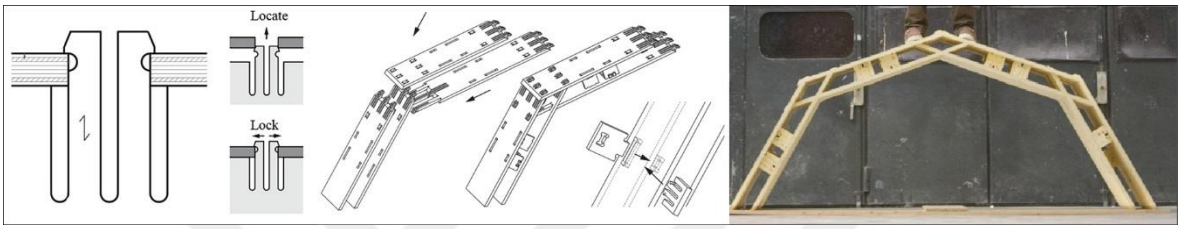


Figure 4.14. Snap-fit joint prototype by Christopher Robeller, (a) snap-fit joint, (b) assembly of the arch prototype (c) physical prototype single-folded double-layer arch (Robeller et al., 2014)

In this case study, the proposed elastic joint has the following advantages:

- The main parameters for the clip-tenon joints are length, thickness, deflection and dimensions. There are many types for snap-fit designs; the one used for clip-tenon joints in this structure is the cantilever snap-fits design illustrated in figure 4.13.
- Being a separate part of the plate, any damage to the joint will not affect the whole plate.
- It is easy to transfer, assemble and disassemble for endless times.
- It can be easily fabricated from a laser cut machine, which is considered a simple machining compared with other CNC machines usually used for wood manufacturing such as CNC router; over-machining and fabrication is avoided.
- The parametric joint can adapt to any folded plate surface with differentiated angles between plates.
- The application of this joint works regardless of the material of the plates used. Although the joint relies on elasticity characteristic of wood which limits the choice of materials mainly to plywood, but this does not apply to the materials from which the plate is being cut. Having the joint dependent from the plate gives wider options when choosing the plate material.

Procedure

For this case study, the procedure in figure 4.15 was followed. The parametric joint and the shell geometry were developed in two separate steps, and the joint was projected on the shell's base surface. The steps are explained in details in the following sections.

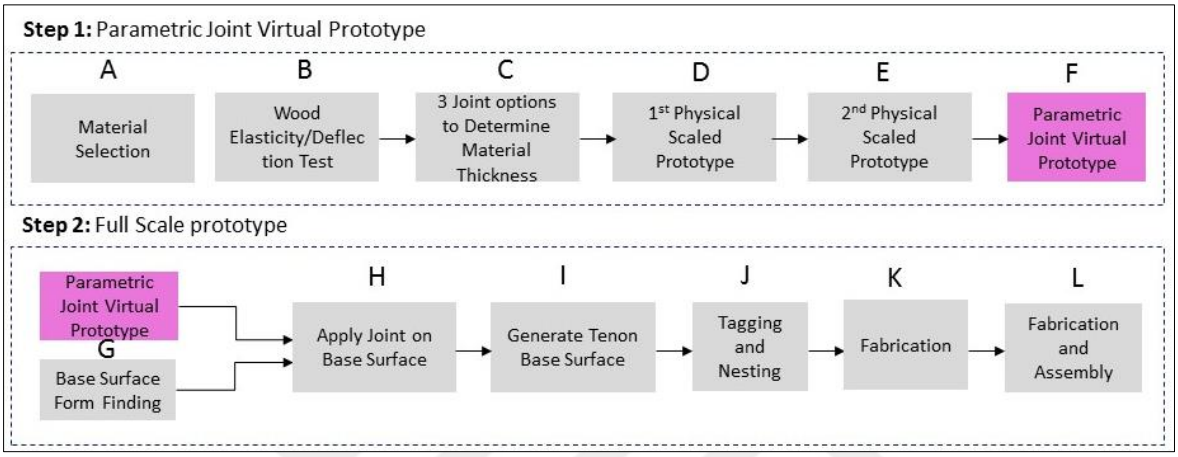


Figure 4.15. Third case study procedure

4.3.2. Material selection

Birch Plywood, 5mm, 6mm and 9mm thickness, was used for manufacturing the different joint prototypes and the final joint was made from 6mm thickness. Table 4.1 shows the used material's properties.

Table 4.1. Birch plywood technical characteristics (Segezha Group, 2016)

Index	Unit	Actual value
Shear strength (adhesive strength)	MPa	2,2
Ultimate bending strength parallel to grain	MPa	72,1
Ultimate bending strength perpendicular to grain	MPa	62,7
Modulus of elasticity bending parallel to grain	MPa	8571
Modulus of elasticity bending perpendicular to grain	MPa	6726
Moisture content	%	7,2

4.3.3. Wood elasticity/ deflection test

To make an informative decision about beam width, the test shown in figure 4.16 was made to find the deflection at certain intervals along the beam. Measurements were taken at points a,b,c,d,e and f. The deflection here represents the possible length of the permissible undercut at these length intervals.

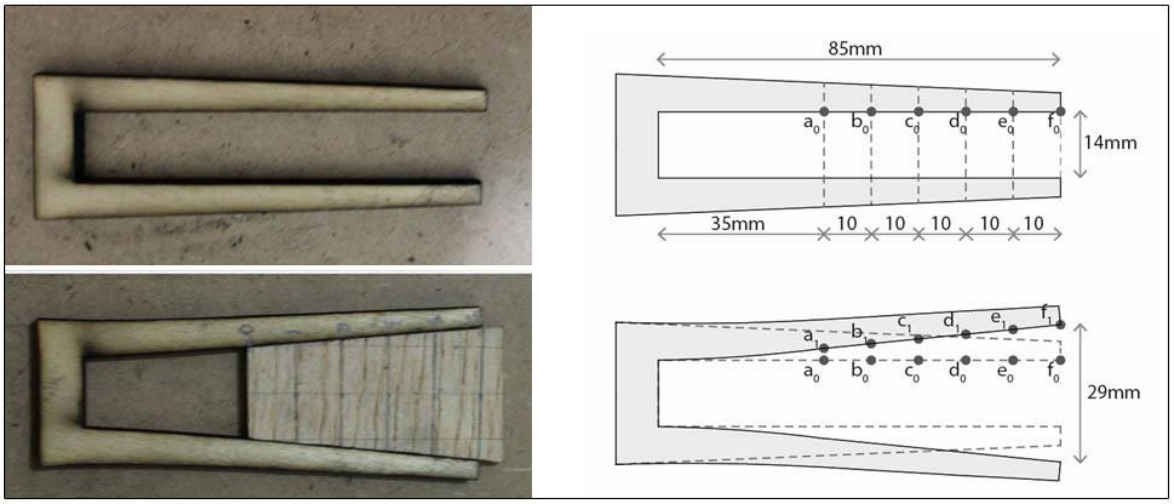


Figure 4.16. Deflection test

For the following plywood piece of 5.5 mm thickness, the deflection values were as in table 4.2:

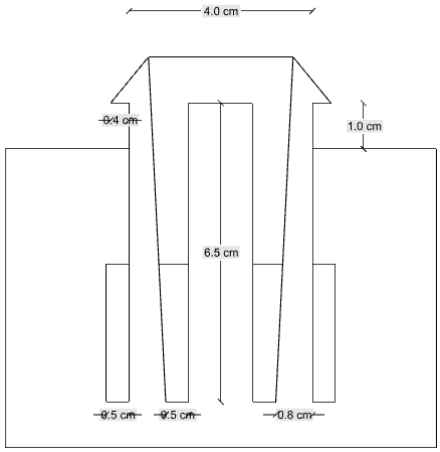
Table 4.2. Deflection values for 5.5 mm thickness plywood

Point	Distance from base (mm)	Displacement	Deflection (mm)
a_0	35	$a_0 - a_1$	2.5
b_0	45	$b_0 - b_1$	3.5
c_0	55	$c_0 - c_1$	4.5
d_0	65	$d_0 - d_1$	5.5
e_0	75	$e_0 - e_1$	6.5
f_0	85	$f_0 - f_1$	7.5

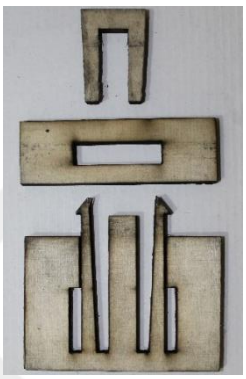
4.3.4. Single joint options

Three options were prepared to find out the best combination of deflection value to beam length and material thickness as illustrated in tables 4.3, 4.4, and 4.5.

Table 4.3. Single joint- option one







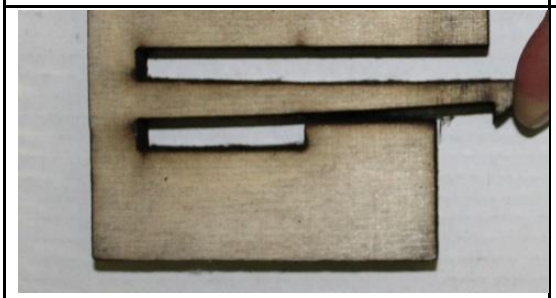
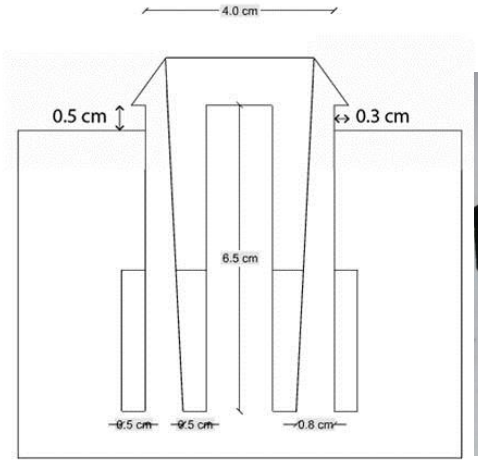
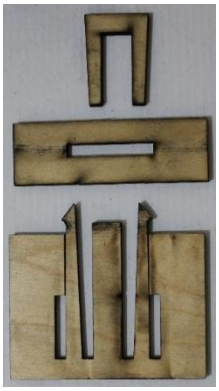
Material	Birch plywood
Thickness	9 mm
Beam Length	65 mm
Base Width	8 mm
Under Cut Width	4 mm (3 mm after the laser cut)
Tenon Dimensions	10 X 41 mm (added tolerance of 0.5 mm to allow for interlocking)
Maximum Deflection	3.5mm
	Observations**:** 0.5 m as added tolerance from each side of tenon is more than what is needed for a tight fitting. This resulted in the material not be totally fixed in its place. Using laser cut is not favored for this thickness.for this thickness.

Table 4.4. Single joint- option two







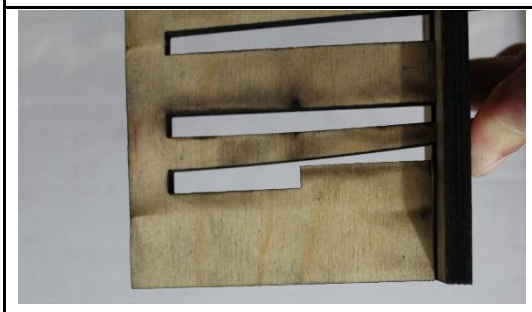
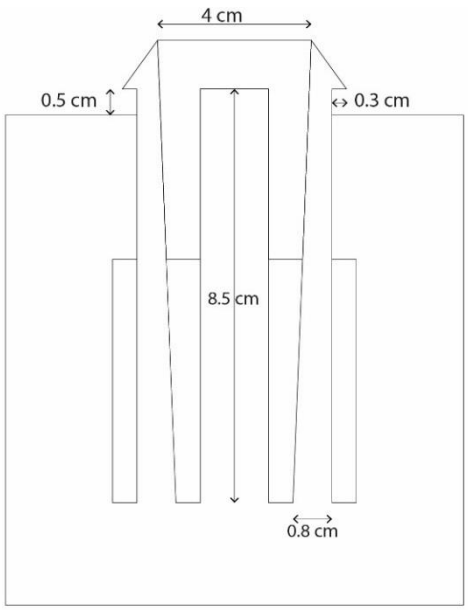
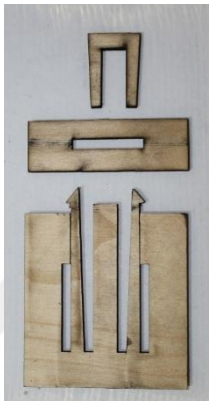
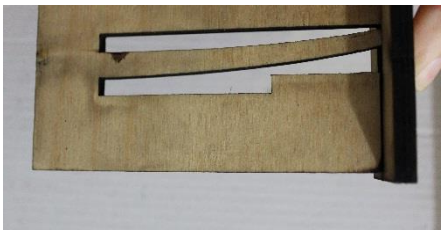
Material	Birch plywood
Thickness	5.5 mm
Beam Length	65 mm
Base Width	8 mm
Under Cut Width	4 mm (3 mm after the laser cut)
Tenon Dimensions	10 X 41 mm (added tolerance of 0.5 mm to allow for interlocking)
Maximum Deflection	5 mm
	Observations: 0.5 m, as added tolerance from each side of tenon, is more than what is needed for a tight fitting. This resulted in the material not be totally fixed in its place.

Table 4.5. Single joint- option three







Material	Birch plywood
Thickness	5.5 mm
Beam Length	85 mm
Base Width	8 mm
Under Cut Width	4 mm (3 mm after the laser cut)
Tenon Dimensions	5.5 X 41 mm (tolerance 0.5 mm to allow for interlocking)
Maximum Deflection	7 mm
	Observations: 0.5 m, as added tolerance from each side of tenon, is more than what is needed for a tight fitting. This resulted in the material not be totally fixed in its place.

It was found that the third joint, i.e. the joint with thinner plywood (5.5mm) and longer beam length (85mm), is the one with the highest deflection value. The joint was developed from single clip and tenon to a double clip and tenon where two adjacent panels perpendicular to the joint can be joined.

4.3.5. First physical scaled prototype

The first prototype geometry was created from a double curved surface which was later rationalized into 4 planar 4-edge surfaces. The four plates were the host geometry for the articulated prototype plates. The joint with thin plywood (5.5mm) and longest beam length (85mm) was the one with the highest deflection value (After that the angles between each two surfaces were measured as in figure 4.17 and the third joint with the drawings of the plates and joints were prepared as seen in figure 4.18.

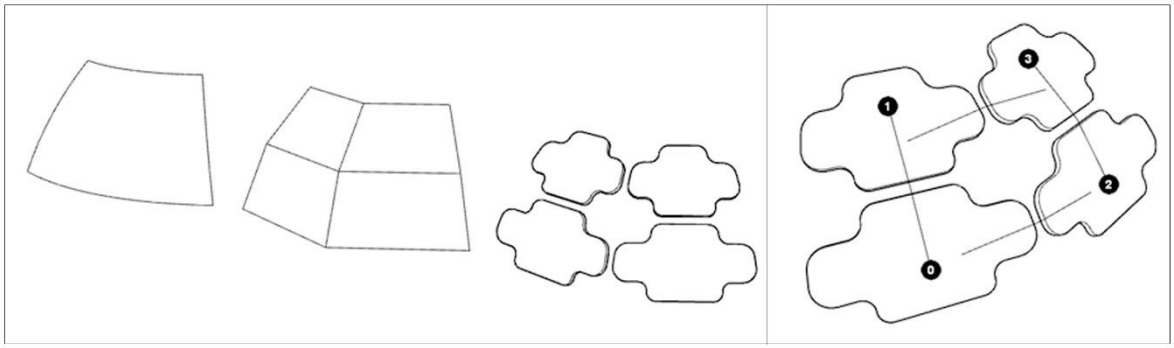


Figure 4.17. Double curved surface from four quadratic plates

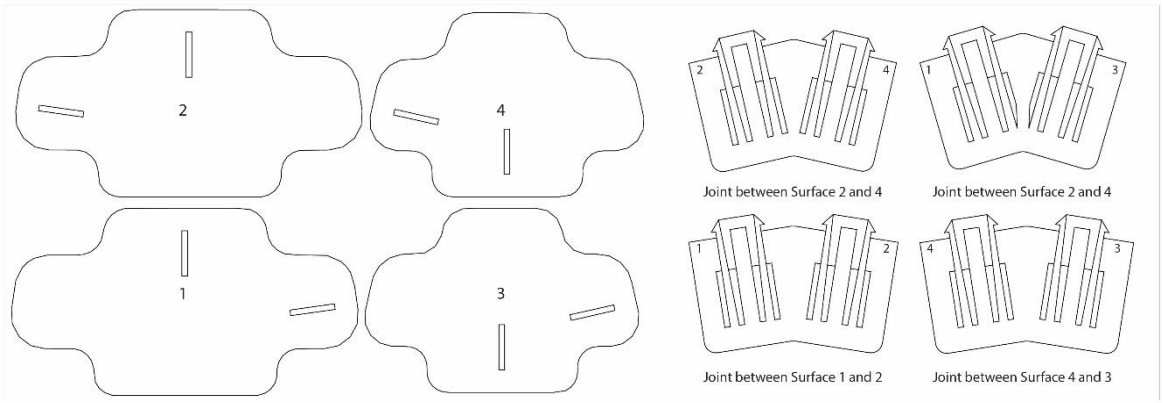


Figure 4.18. First physical scaled prototype: plates and joints

Plates and joints were cut using laser cut-machines, two layers of 3mm medium density fiberboard (MDF) material were used for the plates, and 5.5 mm plywood for the joints and the prototype was assembled as seen in figure 4.19.



Figure 4.19. Fabricated first physical scaled prototype

It was observed that although it was possible to achieve a tight joint and stiff assembly, the prototype itself was heavy in comparison to the thin plates' MDF material. Joint number 3 that was used for this prototype had a beam length of 85m, and this resulted in having large and heavy joints to connect thin and light plates. The beam could not be that long; it was noticed from the prototype that this would cause the joint length (Y) to be more than (12 cm). This way, the joint would consume more material and at the same time its load would not be properly distributed, because it might bend under load and drag the plates downward.

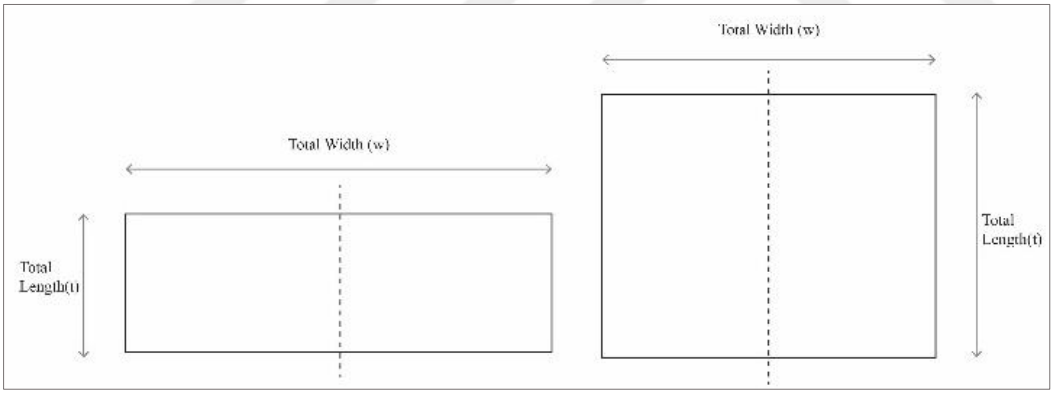


Figure 4.20. Joints appropriate length to width ratio (left) versus undesired length to width ratio (right)

Another five joints were then developed with the aim to acieving less amount of material, lighter weight, a shorter joint depth and a better width to length ratio.

4.3.6. Second physical scaled prototype

In the first and second joints (between plates 4 and 3) and (between plates 1 and 3), it was decided to divide the beam length in two inner and outer arms so the joint length would be shorter and a stable connection would be achieved. However, the first joint between (panels 4 and 3) cracked because the beam was very short, and the second joint (between plates 1 and 2) and third joint (between plates 2 and 4) failed because the beam was long and the arms opened in an outward direction as a result of plate's weight, see figures 4.21 and 4.22.

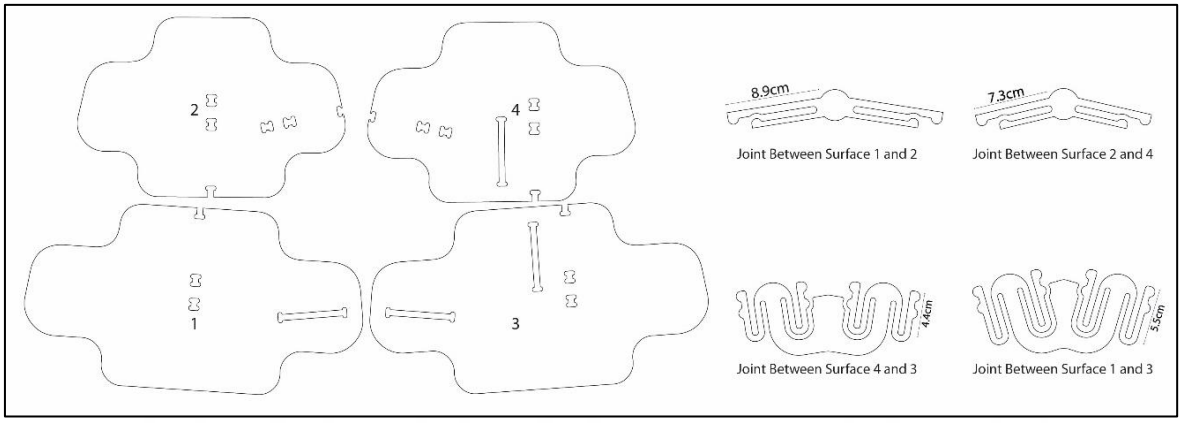


Figure 4.21. Second physical scaled prototype: plates and joints drawings

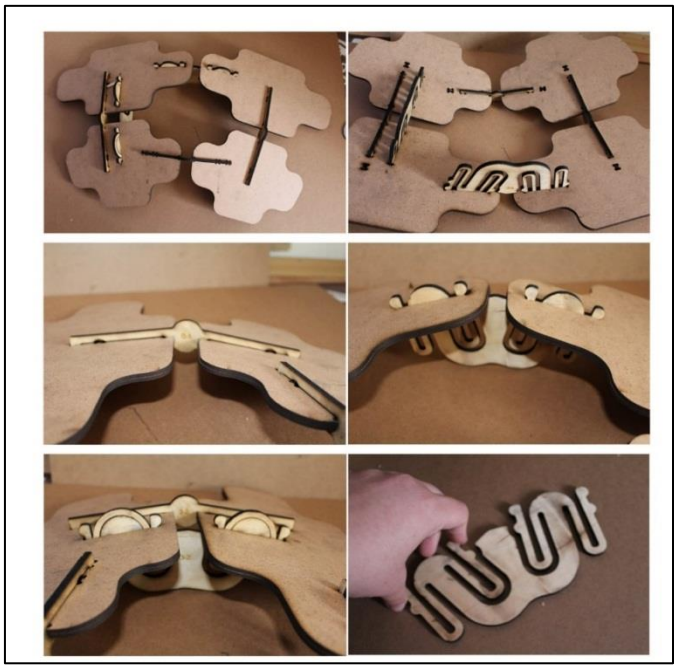


Figure 4.22. Fabricated second physical scaled prototype

Following the previous tests and attempted joint prototypes, it was possible to build on all of that to design the clip-tenon joint. Figure 4.23 illustrates the final design of the joint at an angle of 180 degrees between two plates with its related parameters.

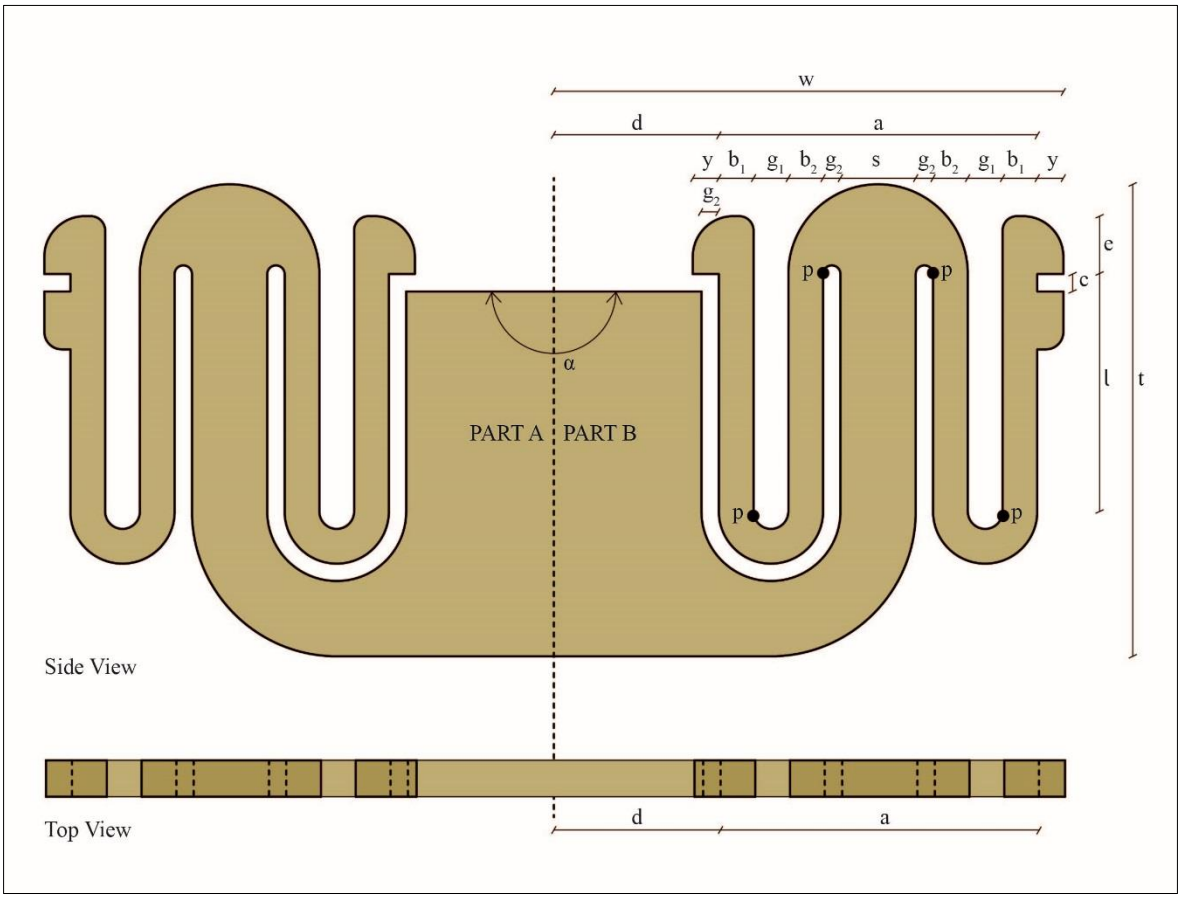


Figure 4.23. Clip-tenon joint anatomy and parameters

w = overall width
t = overall length
d = distance between plate edge and the start of tenon
a = tenon length
l = outer arm length
e = outer head length
c = plate's material thickness
p = outer arm's rotation point
y = deflection (undercut length)
α = angle between plates
b1 = clip's outer arm width
b2 = clip's inner arm width
g1 = arm's inner gap
g2 = arm's outer gap
s = middle segment's width

4.3.7. Parametric clip -tenon joint

Using the different parameters of the tested joints in the previous two prototypes, a parametric clip-tenon joint definition was developed using grasshopper. The definition allows for flexibly testing different options for joint geometry based on major and minor parameters. The major parameters are the distance between plate edge and the start of tenon (d), the outer arm length (l), plate's material thickness (c), required undercut length (y), the angle between two plates (a), inner and outer gaps (g1 and g2), and middle segment's length(s). The minor parameters are clip's head length (e), fillet radiuses, and additional value for controlling inner arm length. The values can be changed to reach an optimized balance between material usage, stability of joint and maximum support for the plate. Figure 4.24 shows the input, process, and output for the definition, while figure 4.25 shows a series of iterations generated from the same definition.

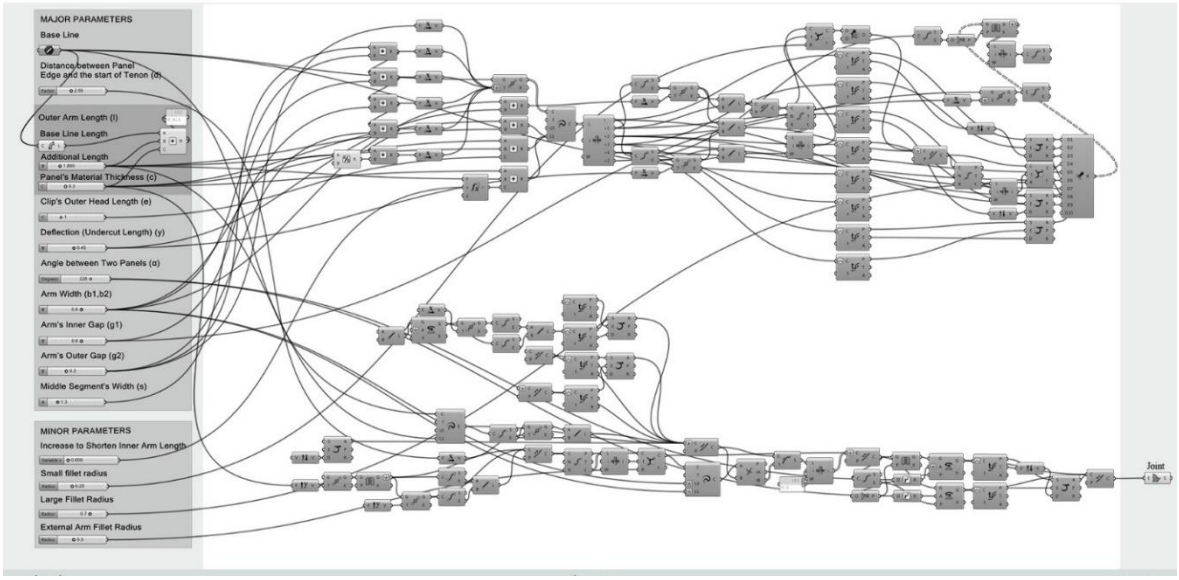


Figure 4.24. Parametric clip-tenon joint Grasshopper definition



Figure 4.25. Clip-tenon joint: iterations

Distance (d), length (l) and gap parameters (g1 and g2) control the range of minimum and maximum angles that can be covered. If the angles in the pavilion cover a wider range (for example from 0 to 360), then distance (d) must be increased. Although it is possible to create joints with any value for angle (α) between plates, yet for this structure and for the purpose of unifying the overall width value (w) for the 45 joints, and to reach an optimized solution where the least possible amount of material is used, distance (d) was fixed to a value of 2.55, which is enough to cover the range of angles found in the pavilion. By doing so, the 45 joints' overall width (w) became unified. The angle between any two plates in the pavilion is within the range of 80 to 230 degrees (figure 4.26). If an outside-range angle is required (less than 80 or more than 230), distance (d) and, as a result, the overall width (w) parameters must be changed to avoid to self-intersected or undesired joint geometry, as illustrated in figure 4.26.

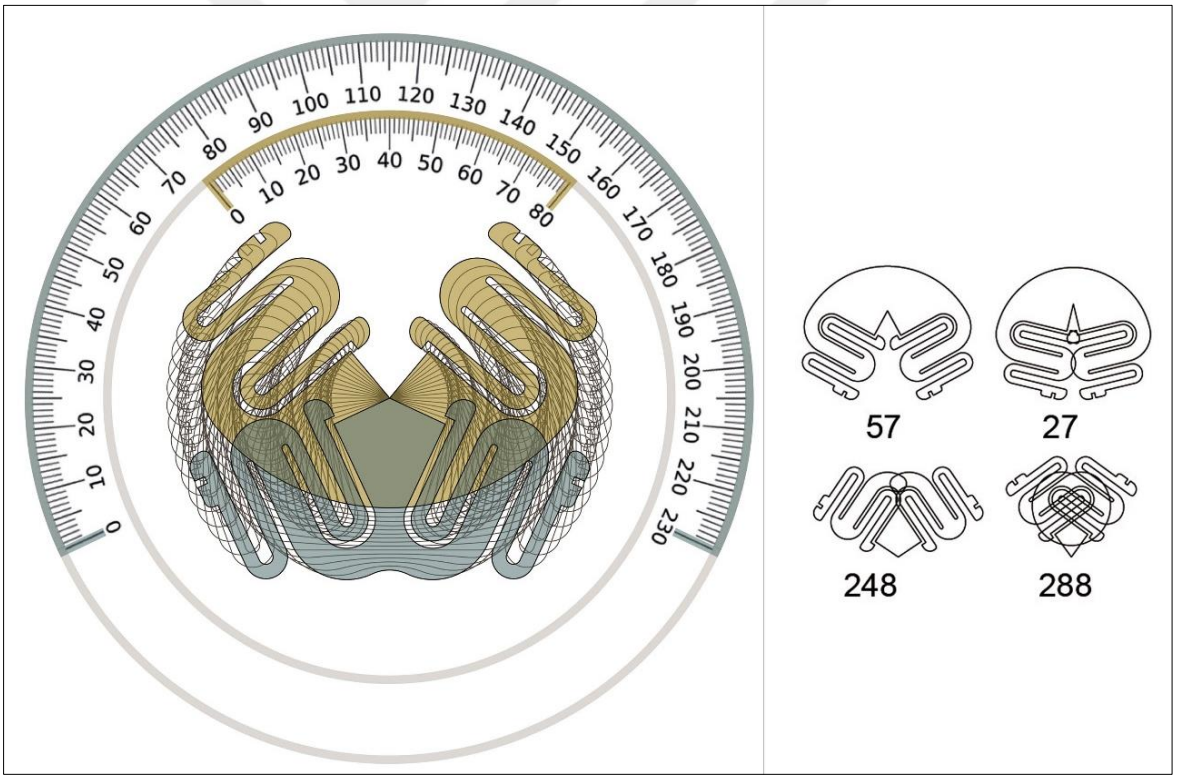


Figure 4.26. Range of Angles Covered when the Distance Parameter (d) Value is Fixed at 2.55 cm and an Example of the Undesired Results Outside this Range

One of the important aspects of the joints design is the position of arch that connects the two inner arms at each side of the joint. In figure 4.27, the illustration to the left shows that when having longer inner arm length, the deflection of the outer arm will stop once it touches the dotted line. In order to allow for more deflection and ease of assembly, the arch

between inner arms was pushed inward but at the same time not in an excessive manner that could cause joint's failure.

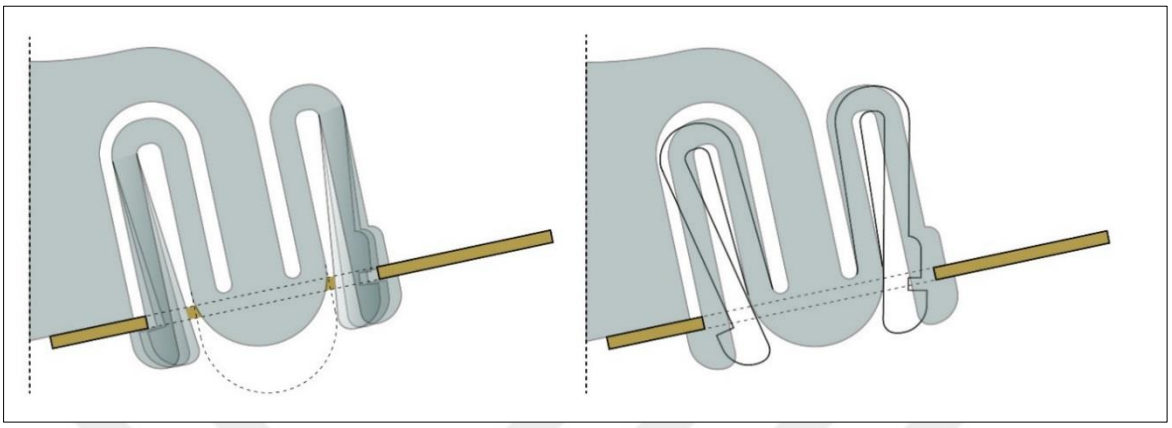


Figure 4.27. Effect of inner arm length on avoiding excessive deflection that might lead to inner and outer arm cracking

Unifying all joints to have the same total length and width was done in order to unify joint's key sizes. The key is a small repetitive piece that does not have an individual size for each one. This won't be feasible for the assembly of the pavilion. The key functions as a stabilizer that prevents joint's arms from being pressed inward again.

4.3.8. Digital form finding

The digital form finding method was used to create a shell from planar quad meshes using parameters optimizing two forces: the load force and the planarization force. When approximating a double curved surface with quadratic paneling, the result will be a non-planer panels. In this research, the shell's panelization must end up in having planar elements so they can be cut from planar boards.

The form finding process shown in figure 4.28 started with creating a rectangular mesh with 4 quads in a U direction and 7 quads in a V direction, and mesh's dimensions represent the real dimensions of the plan. After that, anchor points were defined for a total of 6 points, representing the 4 corners and 2 points at the middle of the rectangle's long edges. Kangaroo plugin utilizes the particle-spring systems for shell design. The purpose of adapting the form finding approach for shell design is to reach an optimized design with minimal material, as seen in figure 4.29. The form finding process resulted in a number of

options by changing the forces parameters values. The aim was to acquire a form where all quadratic panels are planar. There were several options for this and the one with suitable height and panel proportions was selected.

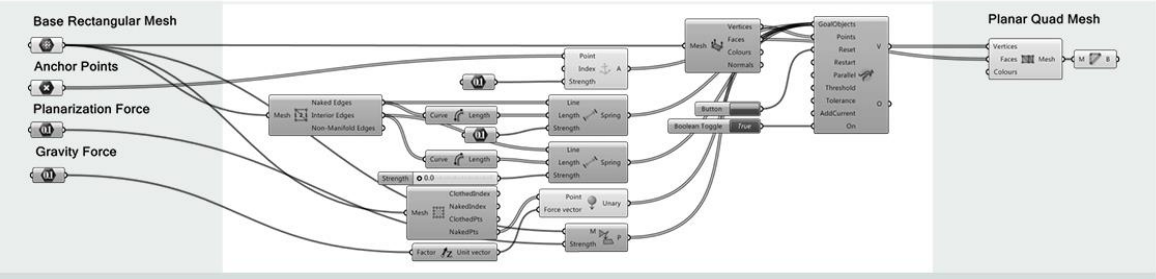


Figure 4.28. Kangaroo form finding definition adapted from Daniel Piker

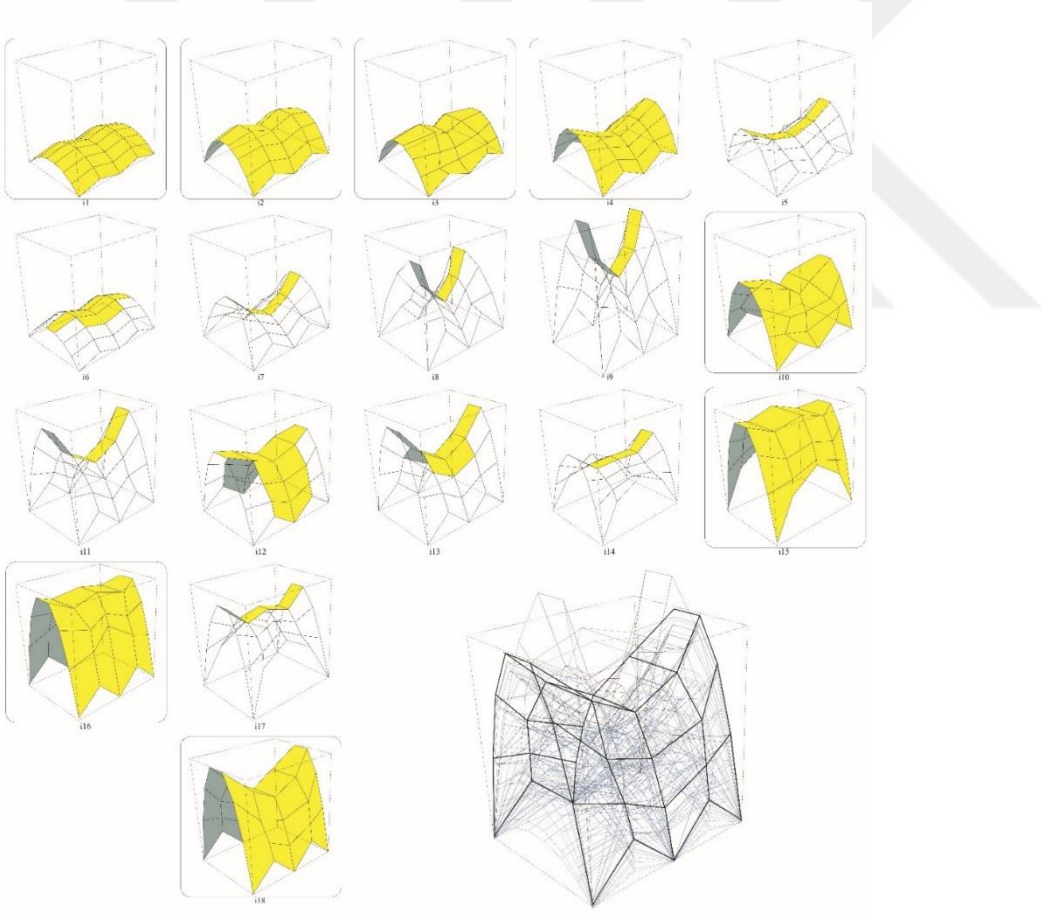


Figure 4.29. Digital form finding for a full scale prototype shell with planar quad mesh, iterations inside the frames is for shell options with fully planar quads

Form finding and planarization enable prefabricated double-curvature structures to be built by limiting all fabrication to only two-dimensional cutting and relying on structural folding to achieve desired geometric forms.

The design of the joint and the form finding process aimed at developing a double curved surface from planar quadratic plates that could be fabricated and connected by relying on two-dimensional cutting only. Both the plates and the joints are planar, thereby preventing over-fabricating processes like milling to connect these non-standard pieces.

The result of the form finding process was a mesh of 28 faces. For easier and better geometry processing and surface Boolean operations, the mesh was converted into 28 untrimmed planar surface following the process illustrated in figure 4.30.

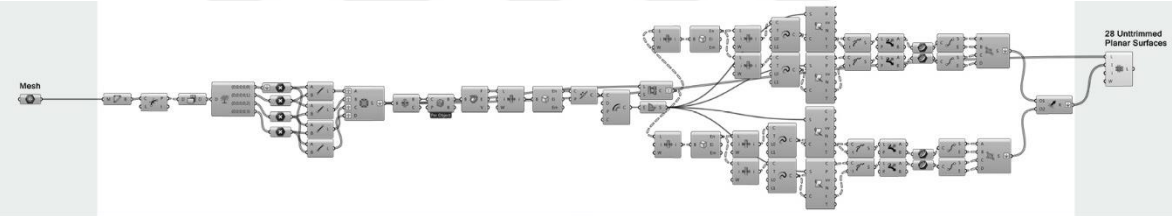


Figure 4.30. Grasshopper definition for generating untrimmed surfaces from mesh faces

4.3.9. Plates boundary mapping and tenons and joints orientation

In this step, two actions were executed. The first is designing the plate's final boundary shape and mapping it on the pavilion's base quad poly-surface and then locating the four tenons, one at each of the plate's egdes. The aim of designing the plate with such corners was to make it easier to grab the plate in one's hand and to fit the joint in the other (or to take it out in case of disassembling the pavilion). By designing it this way, it was possible to avoid the need for any false structure which functions as a support for the incomplete structure during assembly.

Regarding orienting the parametric joint, the location of the three points required for orienting each part of the joint is shown in figure 4.31. The four drawn parts and the mapped plates are the input geometry for the three dimensional orientation process. Parts A and B are for inward joints (located at the structure's inner surface) and C and D for outward joints (located at the structure's outer surface). Out of the 45 joints used in the

pavilion, only one was needed to be changed from outer to inner joint because the angle between the related two plate surfaces was exceeding the limit explained previously in figure 4.26.

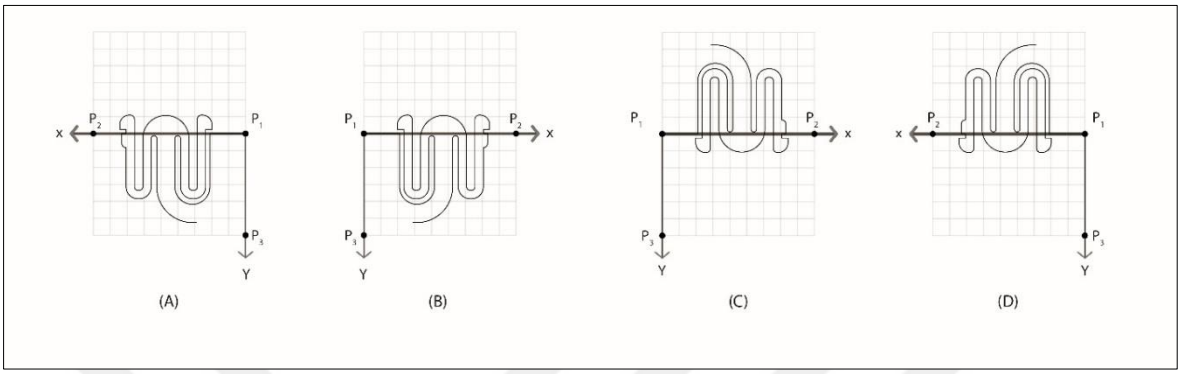


Figure 4.31. Inward and outward joint's orientation planes

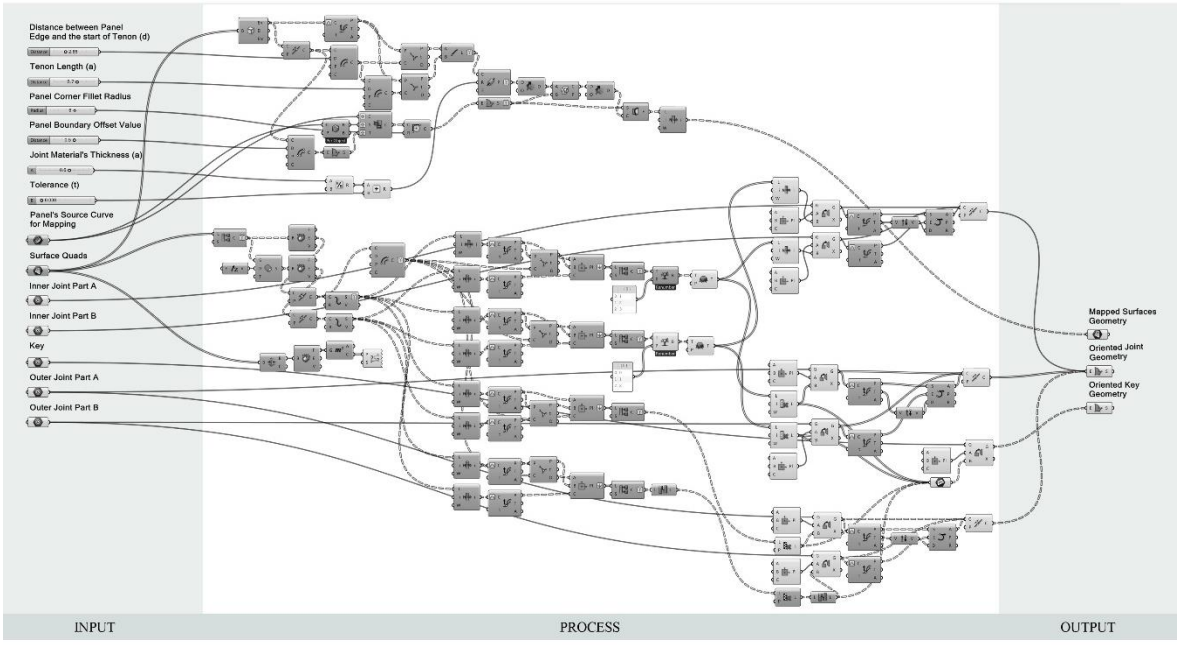


Figure 4.32. Plates boundary mapping, tenons and joints' 3d orientation

The final result was a full scale prototype with 28 differentiated surfaces and 45 joints (see figure 4.33 and figure 4.34).

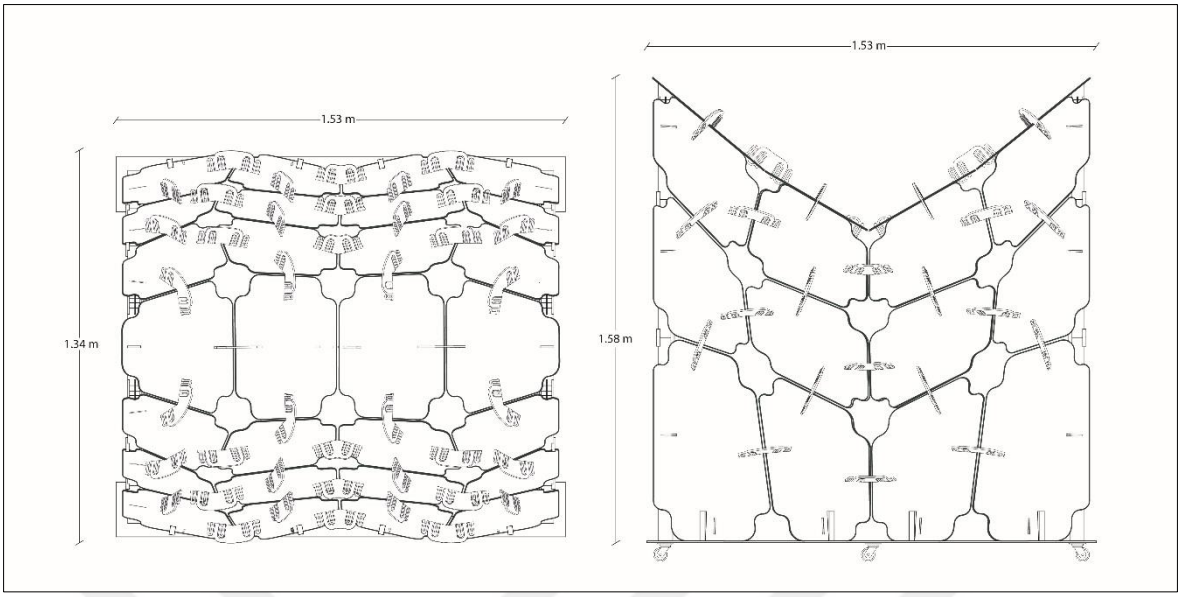


Figure 4.33 Full scale prototype's top view and side view

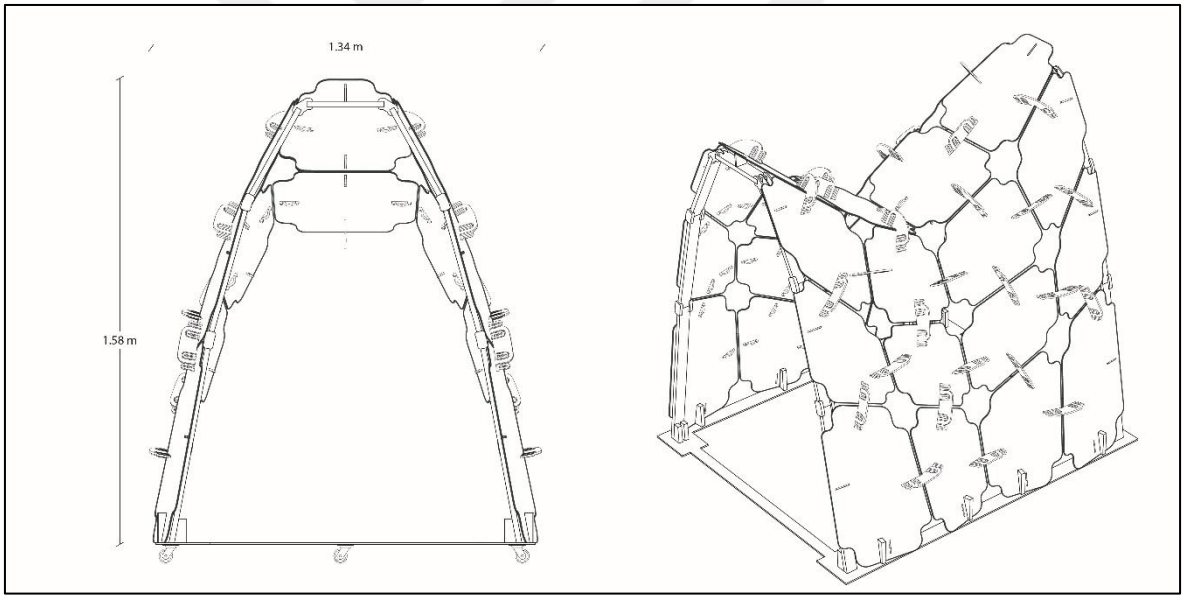


Figure 4.34 Full scale prototype's front and perspective view

4.3.10. Tagging and nesting

This step in the process is concerned with orienting the different geometries from their position and orientation in 3d space into the planar XY plane. Fitting the geometries inside boundaries represent the boards that will be used and generating tags following the assembly logic required for the pavilion. Plates were grouped in 7 rows and for each plate the tag represents the row and the order of this plate, R0-0 being the first plate in the first

row. For the joints, they were grouped in 7 horizontal X rows including 21 joints and 4 vertical Y columns including 24 joints.

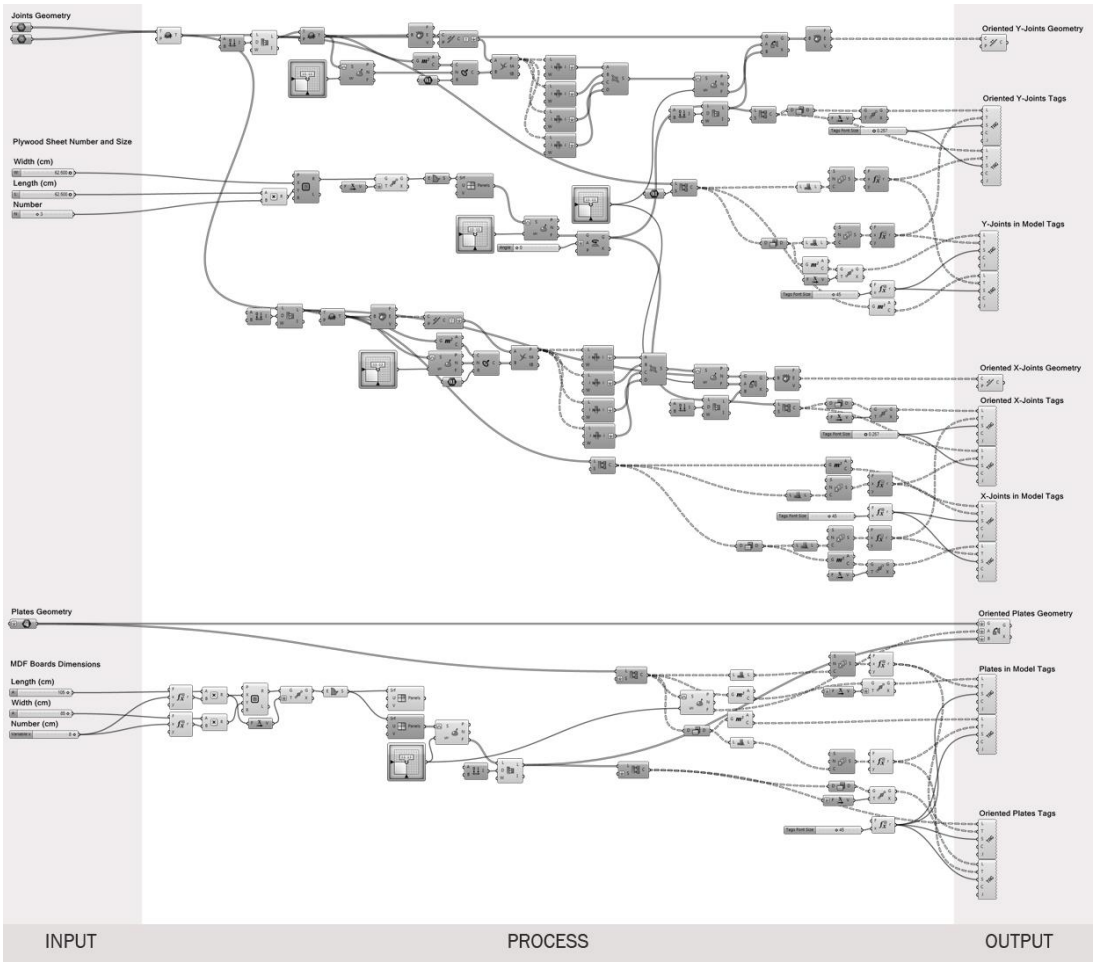


Figure 4.35. Tagging and nesting grasshopper definition

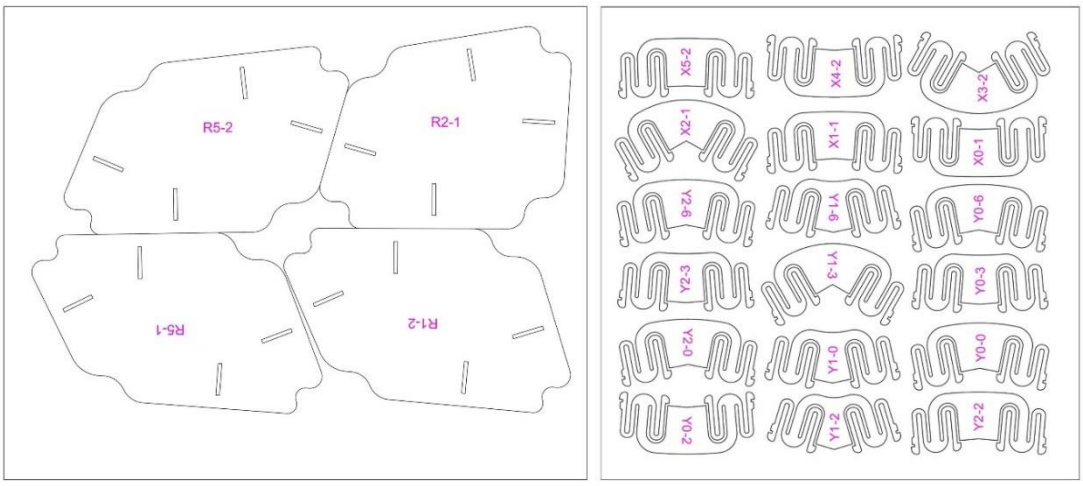


Figure 4.36. Example for the tagging engraved on top of plates and joints (text enlarged for presentation purposes only)

4.3.11. Fabrication

The 28 plates were cut using laser cutter machine with wide bed, thus allowing the use of MDF boards with larger sizes and avoiding waste. The 45 joints were also cut from 6mm plywood using laser cutter. Cutting the joints took more time because the material was thick and very stiff compared to MDF boards. Laser cutter might not be the best solution for cutting plywood in such thickess but laser cutter has the advantage of almost zero vibration and the accuracy of the joint details was very high (see figure 4.37). Figure 4.38 shows the type and size of wood boards and frames that were used. For the frame parts all were cut by conventional machines found in carpentry shops and were assembled with the aid of metal connectors. The whole structure was later raised over wheel casters to make its movement possible.

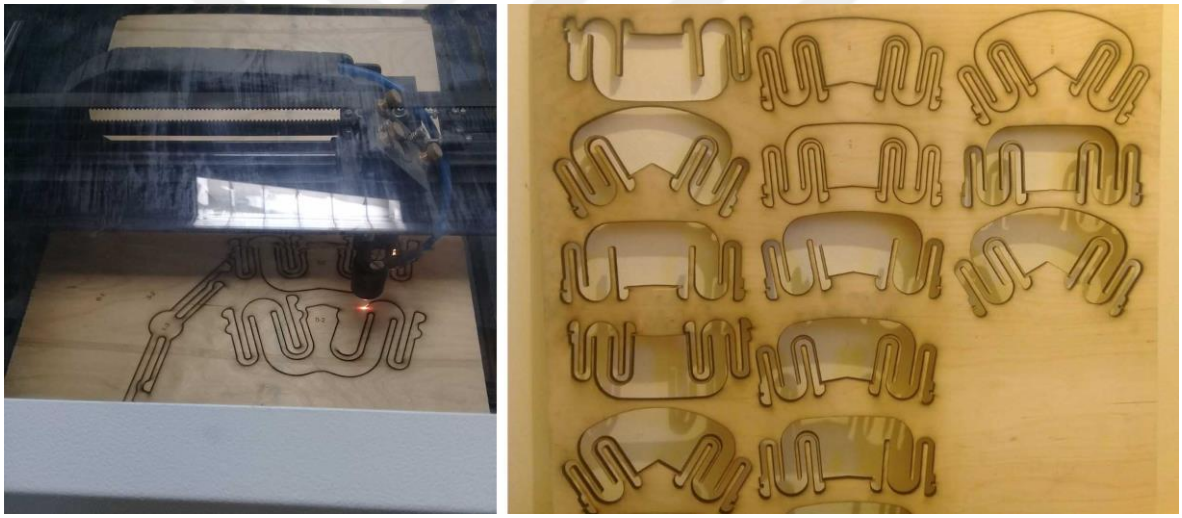


Figure 4.37. Fabrication with laser cut

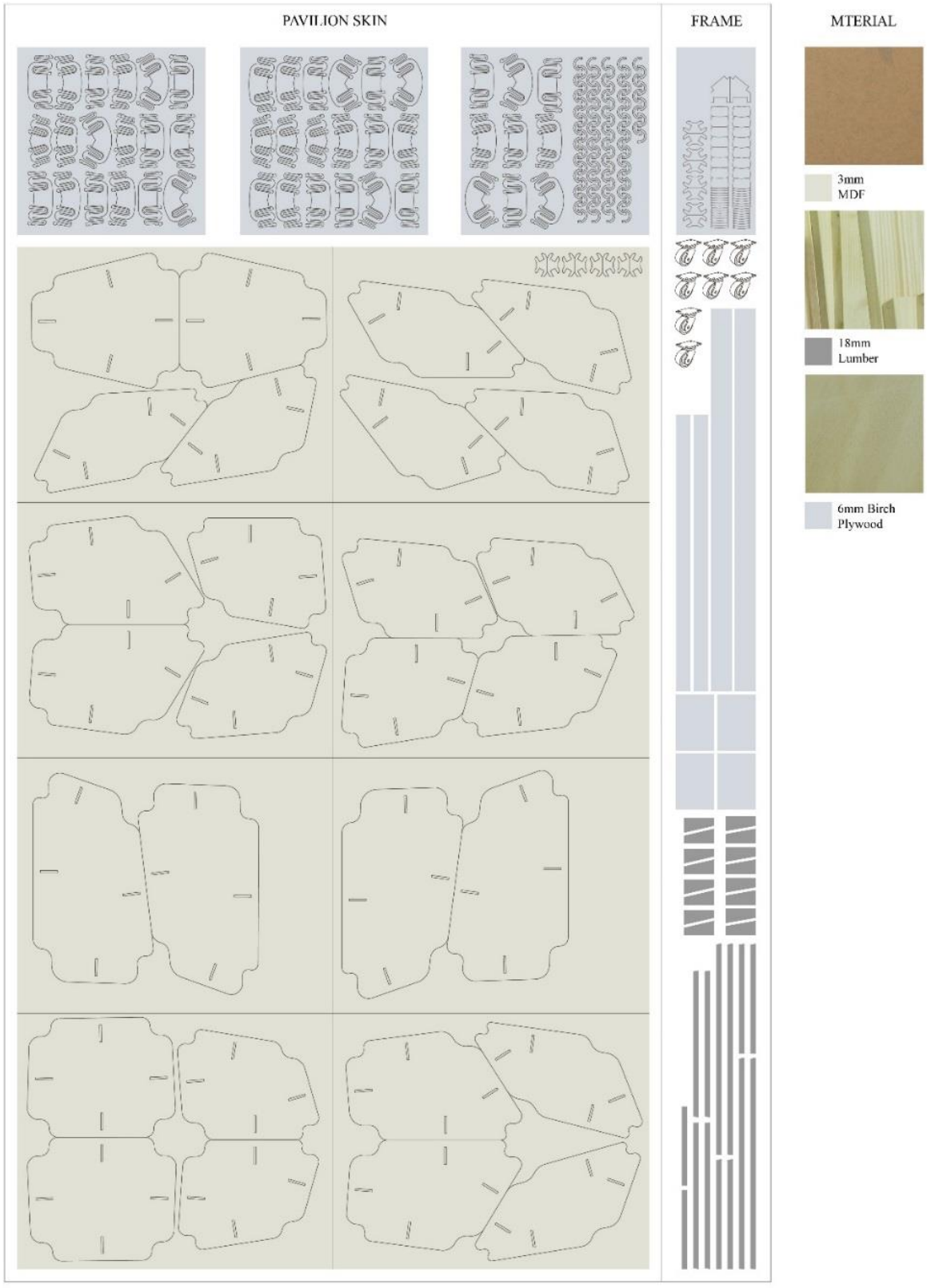


Figure 4.38.Consumed materials for the full scale prototype

4.3.12. Assembly and disassembly

Assembling the full scale prototype started by assembling the frame which had both metal connectors and interlocking joints. Then the plates were attached in order as shown in figure 4.40.

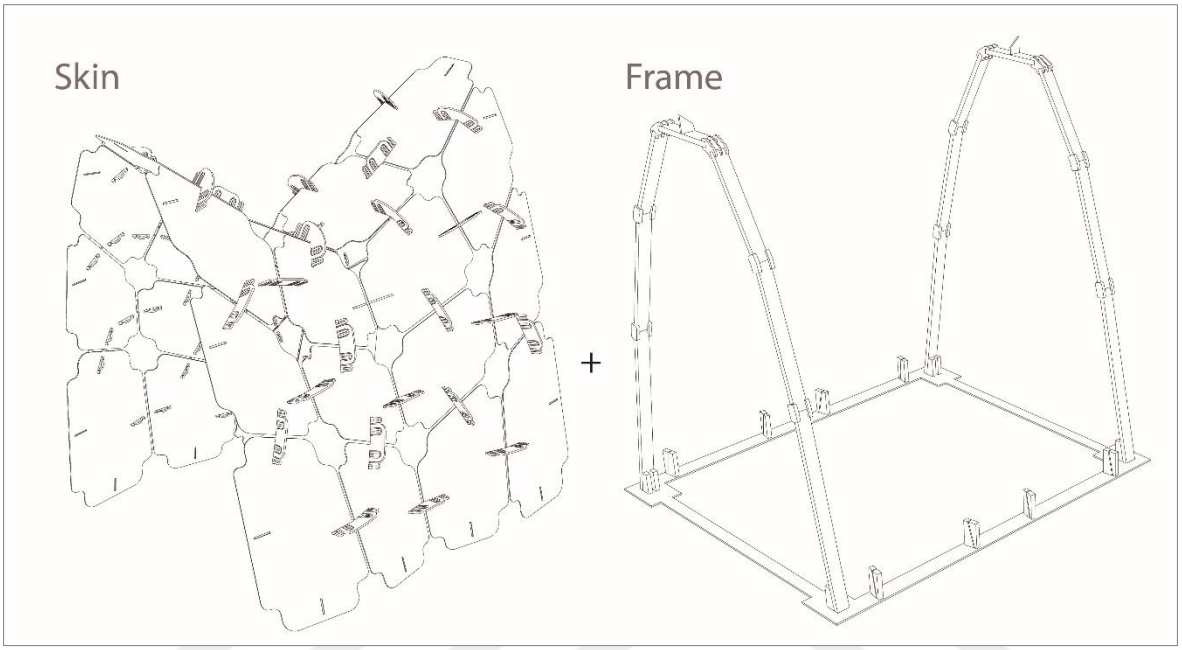


Figure 4.39. Full scale prototype skin and frame

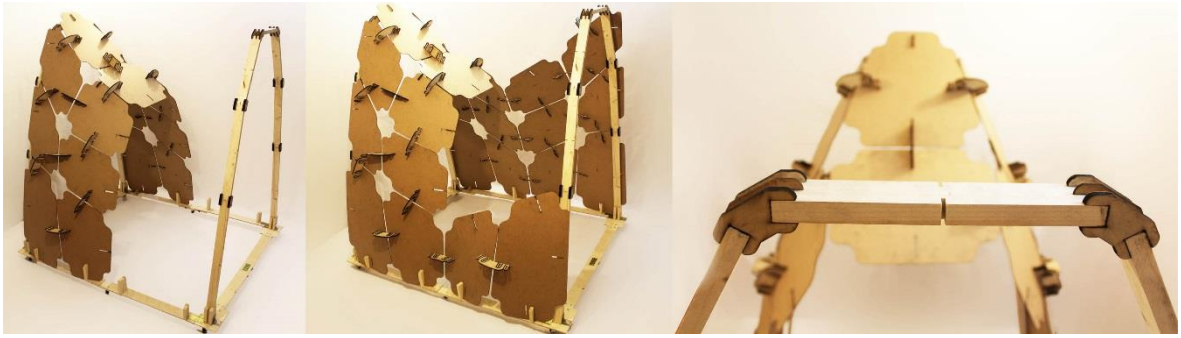


Figure 4.40. Full scale prototype assembly

Disassembling the full scale prototype is as important as assembling it because it proves the idea of the mobility of the structure and the functionality of the designed joint. Disassembly started with the reverse order of the assembly, from top plates and joints to the bottom. The time required for assembly and disassembly was less than one hour. The frame itself was made of 10 groups to make disassembly possible for the frame as well. Disassembly first requires taking out the joint keys and then the joints. The order followed

for disassembly enabled the structure to be taken down without the need for any support structure. Figures 4.41, 4.42 and 4.43 show the full scale prototypes from different angles.



Figure 4.41. Full scale shell prototype with elastic clip-tenon joints

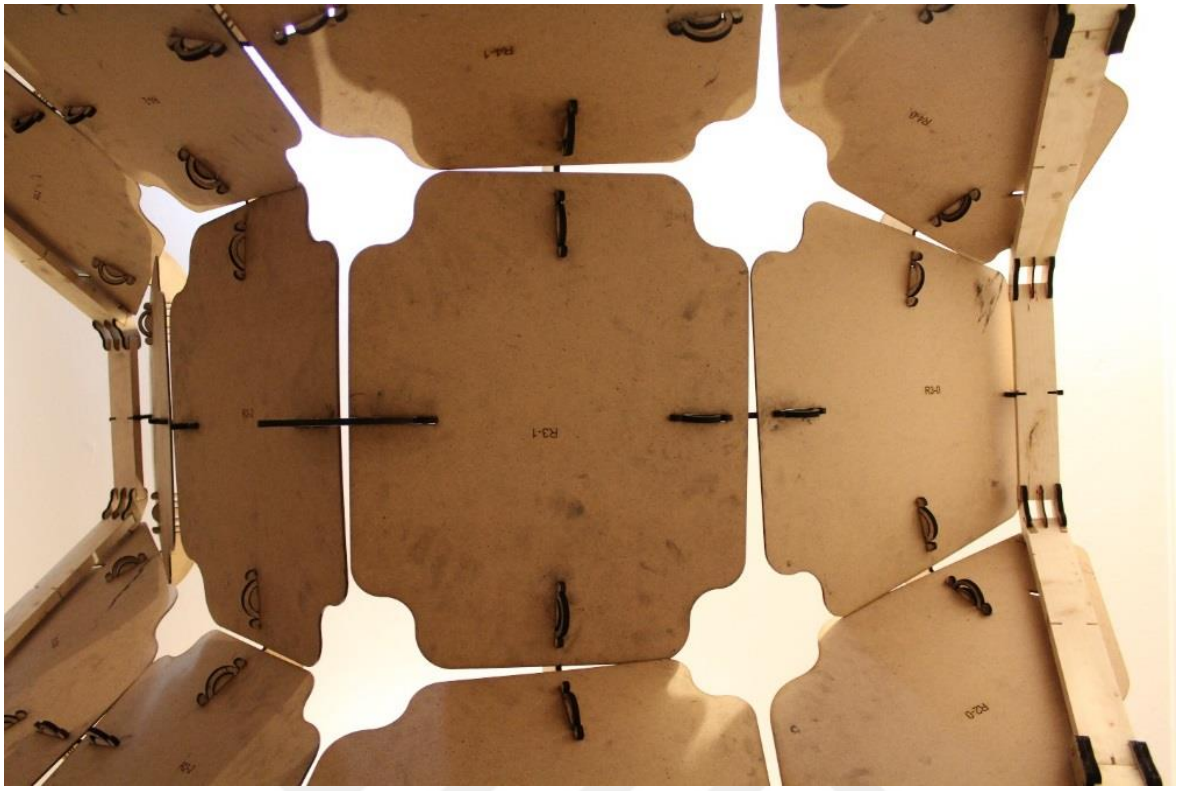


Figure 4.42. Full scale prototype, picture from inside looking up

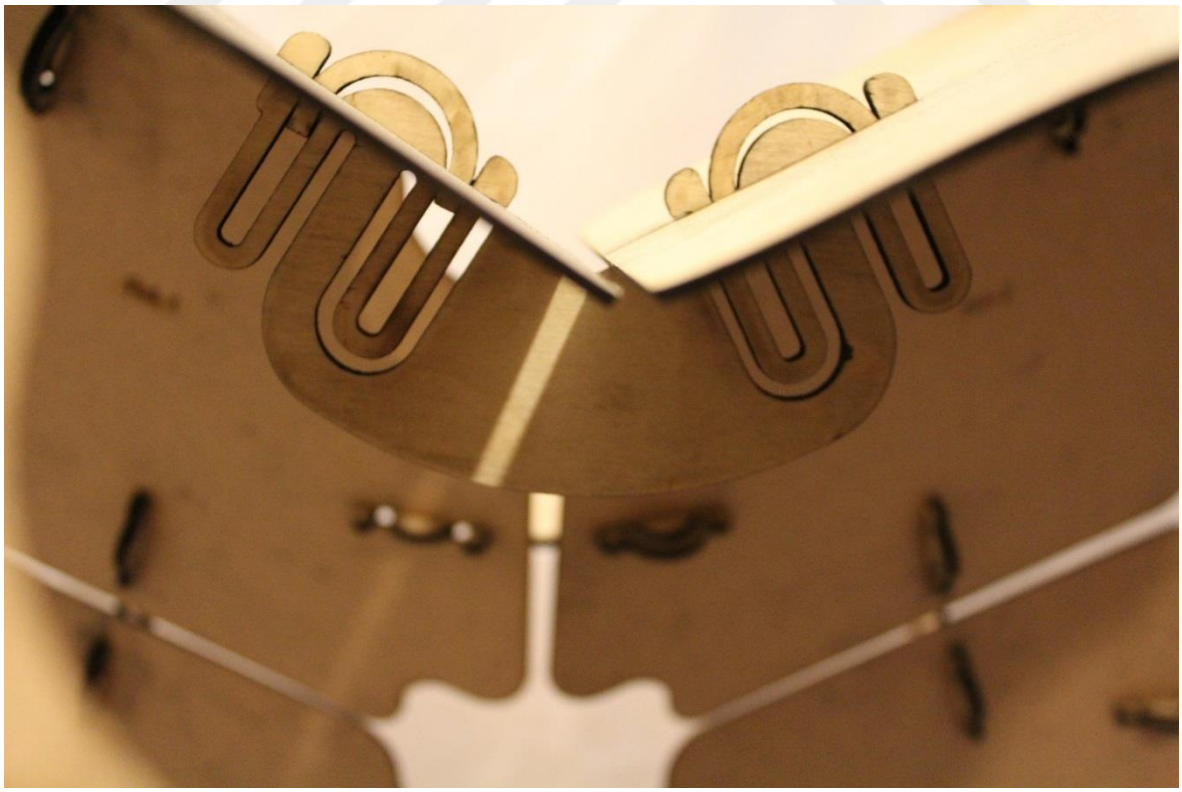


Figure 4.43. Clip-tenon elastic joint, detail for the joint mechanism

5. CONCLUSION

In the last decades, very rapid transformations have been observed in the realm of architecture through computational technologies and changes that occurred in architectural design processes and activities from "design recipes" to "design optimization". The potentials of computational design and fabrication technologies have also altered designers' "material" perception and re-introduced it as one of the main parameters in the architecture of this era.

The focus of this thesis was on wood joinery for the potentials it has on developing material-conscious designs. The main objectives of this research were as follows: (1) to Identify and explore the role of computational design and digital fabrication technologies in designing and manufacturing complex wooden structures making the interlocking wood joinery the main connection type; (2) to develop parametric rigid and elastic wood joints for selected complex geometries of frame members and plates components using parametric modeling; and (3) to fabricate a physical full-scale prototype from wood to test the applicability of the developed elastic clip-tenon joint.

Following the literature review that was conducted, it has been found that advanced technologies offer the chance for developing existing wood joints in addition to creating new joints, the design and fabrication of which would not have been possible before. In the first case study, regarding parametric rigid “halved and lapped” and “mortise and tenon” lengthening frame joints, the methodology for geometry processing was based on defining the joint’s profile by the number of control points. In this way, what started as a parametrizing of traditional joints expanded to produce joints with new profiles that did not exist before. Thus, the application of this definition was not limited to only parametrizing traditional joints that existed before. In the second case study concerning parametric rigid finger-tenon lengthening and cross plate joint for a complex lattice structure, developing the digital prototype of the lattice structure gave an example of how to expand the application of finger joints in plate-based structures. It showed a new area of application for this joint when supported by parametric modelling. The third case study (parametric elastic clip-tenon T-shaped plate joint for a wooden pavilion), is so far one of the few existing examples of elastic wood joinery. The hidden potentials of engineered plywood

material were revealed by cutting the material in a way that allows the elastic properties to be the principle driving both the joint and pavilion design.

The main research targeted the digital prototyping and physical fabrication of three types of joints. However, access to advanced 5-axis physical fabrication machinery was not available for experimental research but only for mass production purposes. Therefore, carrying out this research depended on the available and accessible two-dimensional laser cut machines.

The first and second case studies focused on creating digital prototypes for the complex three-dimensional joinery. A future funded research could expand the topic further to study the applications of these developed joints. The third case study focused on creating both digital and physical prototypes for where elastic joints connect planar non-continuous plates together. Future research may offset this limitation and expand research by using multi-axis advanced machining to achieve continuous surfaces.

There is a number of potential complex interlocking joints research areas. The first is to expand this research to develop material systems that match the demand for a real building components, where the material system is not limited to a single layer of material. Thinking of tightness and isolation as well as integration with other components and openings will make it possible to have a practical application of such proposals in structures and building parts (roofs, façade panels,etc..). The second area of future research is to examine the structural performance of joints and structures and to have structural performance as a fundamental parameter that informs the design of the joints and structures. The third area of potential research is to further expand the research of elastic joints to cover other forms of joints and to develop material systems that combine wood joints with other materials and not limit it to wooden plates or frames. Having the joint in wood as a separable component gives the freedom to make the plates or frames from other light weight materials.

The research of complex structures and associated wood joinery represents a true potential for architects and engineers when looking for alternative sustainable and innovative designs. Architecture based on recipes or prescriptive solutions is no longer sufficient for this era when the use of computational design and digital fabrication technologies has

completely changed the design and fabrication of traditional materials -especially wood and wood joinery-, Its inherent characteristics together with recent computational technologies, "wood joinery" offers a wide perspective for architects when trying to materialize the complexities of this era. The importance of re-searching new tectonics and materialization technologies, and in this regard re-thinking of wood as a “new material” in architecture, raises the potentials of meeting the demand for new refinements in design.

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