Shell Structures in Wood

Technical Research & Testing
Final Report

Prepared for Forest Industry Innovations

April 14, 2015

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I. ACKNOWLEDGMENTS

This project is made possible by funding from Forest Industry Innovations.

II. COLLABORATORS / TEAM

i. COLLABORATORS

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III. PROJECT DESCRIPTION & SCOPE

v. INTERDISCIPLINARY INVESTIGATION

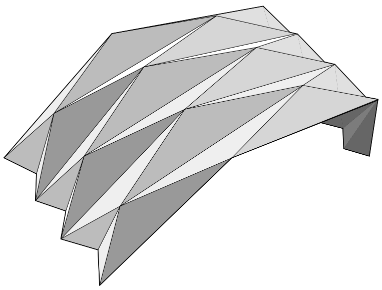

Figure 1. Folded Plate Structure

The larger intention of this research and the future research trajectory is to expand the conception of wood as a structural building material, encouraging its broader use both within Canada and in emerging markets. When architects and engineers desire a curved surface they should think of wood as the material that can create these new architectural forms. Shell, lapped, and folded plate structures using CLT show potential for spanning larger interior spaces such as those in gymnasiums, community centres, schools, churches general large entry spaces and circulation areas. They provide large column free spans, and are highly structurally efficient.

Architects have a new interest in creating curved and flexible surface structures since they now have digital tools which can easily design, draw and produce construction documents for such structures however they have a difficulty manifesting these designs. With current digital fabrication tools, wood has the potential to be the material that is able to easily and inexpensively produce these curved forms. However, research needs to be done in order to demonstrate the feasibility of engineering and fabricating these designs.

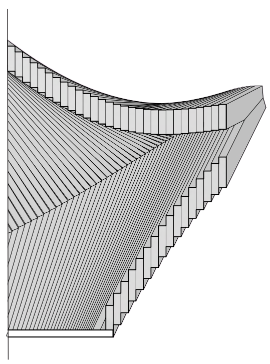

Figure 2. Lapped Panel Structure

The potentials of digital modeling, simulation and fabrication provide the architect with an increased ability to design curved and complex structures. Wood has the potential to respond well and facilitate these designs but this has not yet been fully explored due to the newness of the fabrication technologies and the engineering uncertainties that come along with engineering and fabricating such a structure. CAWP and UBC are well positioned to be leaders and demonstrate the fabrication as well as the engineering techniques for approaching such structures. This research begins the work of demonstrating this new technology and the expanded vocabulary of architectural structures that are possible in wood.

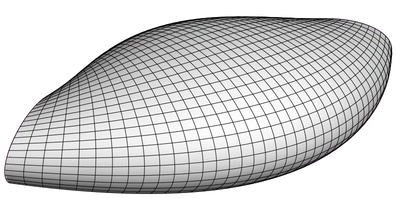

Figure 3. Doubly Curved Shell Structure

In our research, each of the three typologies - the doubly curved shell structure, folded plate structure, and lapped plate structure - (Figures 1,2,3) is being examined under the lens of multiple rubrics relating to the general concerns of architects and engineers. Throughout the course of research each typology has been (or will be) defined in terms of its structural, spatial, and manufacturing limitations, configuration potentialities, suitable connection systems, aesthetics, and behavioral predictability.

To define these properties for each of the typologies have organized our research as follows:

- Structural Research
- Material Limitations (for the doubly curved CLT plate)
- Spatial Limitations
- Configuration Types (Aesthetic Considerations)

- Connection Systems
- Integration of Digital Architectural Models with FEM Models
- Physical Prototypes

vi. RESEARCH PHASES

PHASE 1

The ongoing first phase encompasses research in architectural precedents, structural precedents, material specifications, and parametric modelling / scripting techniques. With this body of reference, we are able to define structural limitations, hypothesize material behaviors, script custom software as needed, and create first iteration digital models. In the first phase of research we are also prototyping a doubly curved CLT panel as a proof of concept on a smaller scale.

PHASE 2

In the second phase we built a larger sectional structure to further test the efficacy of of hypothesized structures. We explored architectural forms in closer detail and start designing the final prototypes. We used a battery of FEM techniques to digitally test our digital models, making new iterations as required.

PHASE 3

In the third phase constructed three final prototypes of our structures: a folded plate wall and two elements of shell structures. The built prototypes demonstrated feasibility and explored problems which required future research.

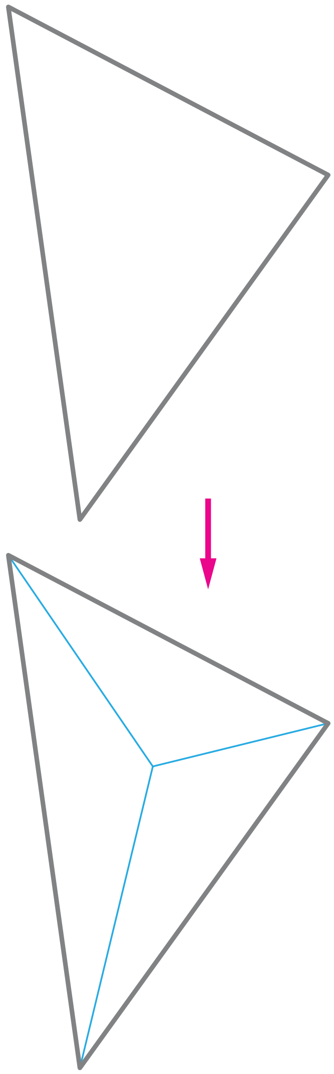

Figure 4. *Panels Simplified as* ***Simply-Supported One-Way*** *Beams* ***(Shown in*** *Blue)*

IV. STRUCTURAL RESEARCH

vii. MATERIAL BEHAVIOR

CLT panels are characterized by alternating laminations of wood which provide high bi-axial in-plane strength and shear resistance. As such, a CLT panel is analogous to a precast concrete slab and has similar design potential. Nevertheless, in recognition of the orthotropic material properties of wood, grain orientation with respect to loading direction must always be considered in the initial stages of design for CLT panel structures. In the execution of this preliminary structural investigation the following assumptions have been made:

i) The Effective Bending Stiffness (EI)eff and Effective Shear Strength (GA)eff of each panel type were calculated based upon Kreutzinger's Shear Analogy provided in the CLT Handbook produced by FPInnovations[1] .

ii) Lamina consist of Douglas-Fir-Larch timber, grade No. 2 or better: material properties are taken from the Canadian Wood Design Manual CSA-O86 2010.

iii) Forces lie parallel to the major grain orientation: however, a material Grasshopper component has been written in Python which takes any grain angle into account, and has been calibrated based upon Strut-and-Tie method estimates and experimental result [2].

viii. SYSTEM BEHAVIOR

While CLT panels may be required to behave as two-way slabs, it is not only easier but also conservative to assume one-way behavior for most cases[3] and therefore individual panels have been simplified as simply-supported one-way beams. (Figure 4.) What follows is that curved or folded CLT plate structures be modeled conservatively as gridshell or complex truss assemblies, which simplifies digital form-finding and finite element analysis.

ix. MINIMUM PANEL SIZE AND MAXIMUM CURVATURE

Geometric morphologies and mutations will require cutting standard CLT panels into smaller angled shapes and sections. Usual design protocol sizes CLT panels for expected loads, yet at the outset of an architectural design potential configurations and their associated loadings are still unknown. Therefore, preliminary guidelines for minimum panel dimensions have been based upon the following criteria:

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1. Gagnon & Pirvu, 2011
2. Pearson, 2012
3. Gagnon & Pirvu, 2011, 2.3.5 p141

i.) DEFLECTION: PANEL SPAN

Deflection calculations considered the weight of the panel itself only. CSA-O86 permits a maximum deflection of L/180 for members all loads, including live loads, superimposed dead loads, and self-weight, but offers no deflection criteria for self-weight alone. A reasonable self-weight deflection limit of L/720 was estimated by subtracting the CSA live load deflection limit from the CSA total load deflection limit. A summary of these span-deflection limitations are given in table 1.

DEMONSTRATION STRUCTURE

		Curvature Radius Limit	Deflection Limit	Max Span	Associated Max Deflection	Minimum Panel Length or Breadth
Total Thickness	39 mm					
Lamination Thickness	13 mm	2200 mm	L/720	3,021 mm	4.20 mm	300 mm
Number of Laminations	3					

STRUCTURE WITH STANDARD STRUCTURLAM PANELS

SLT3		Curvature Radius Limit	Deflection Limit	Max Span	Associated Max Deflection	Minimum Panel Length or Breadth
Total Thickness	99 mm					
Outer Lamination Thickness	32 mm	8500 mm	L/720	5,960 mm	8.28 mm	300 mm
Inner Lamination Thickness	35 mm					
Number of Laminations	3					
SLT5		**Curvature Radius Limit**	**Deflection Limit**	**Max Span**	**Associated Max Deflection**	**Minimum Panel Length or Breadth**
Total Thickness	169 mm					
Outer Lamination Thickness	32 mm	8500 mm	L/720	8,174 mm	11.35 mm	600 mm
Inner Lamination Thickness	35 mm					
Number of Laminations	5					
SLT7		**Curvature Radius Limit**	**Deflection Limit**	**Max Span**	**Associated Max Deflection**	**Minimum Panel Length or Breadth**
Total Thickness	239 mm					
Outer Lamination Thickness	32 mm	8500 mm	L/720	9,871 mm	13.71 mm	900 mm
Inner Lamination Thickness	35 mm					
Number of Laminations	3					
SLT9		**Curvature Radius Limit**	**Deflection Limit**	**Max Span**	**Associated Max Deflection**	**Minimum Panel Length or Breadth**
Total Thickness	309 mm					
Outer Lamination Thickness	32 mm	8500 mm	L/720	11,424 mm	15.87 mm	1,200 mm
Inner Lamination Thickness	35 mm					
Number of Laminations	3					

ASSUMPTIONS:

“Flat Plates, no curvature or precamber
Simply Supported
Douglas Fir grade No 2++, Parallel to Major Grain Orientation

“”Self Weight”” assumes uniform weight of the plate only;
has a deflection limit of L/720
Structurlam Panels are max. 3.0m x 12.2m x 309mm”

Table 1. *Deflection: Panel Span*

However, as stated previously, this investigation is considering panels which are intended to act in concert in a shell structure: considerations for panelized shell behavior must also be respected by the designers and are ongoing, but some semi-rigid connection behavior should be expected which would produce smaller deflections.

ii.) THE ARCHITECTURAL IMPLICATIONS OF PANEL SPAN: CASE STUDIES

Architectural precedents should be taken into consideration when working with a certain panel system, and as such we have taken inventory of multiple community centers throughout the Vancouver area. The community center and its athletic facilities provided a good measure of how far our engineered timber shell structures should span. We will use these centers as rubrics to measure and visualize which of the three panel typologies - doubly curved, pleated, or lapped - is suitable for different sized programs.

Facility	Amenities							
	Pool	Sauna / Whirlpool	Ice Rink	Basketball Court	Dance Studio	Child/Youth Center	Fitness Center	Racketball
Kitsilano	no	yes	200'x85' (100)	no	yes	yes	yes	no
Britannia	25m	yes	200'x85' (500)	no	no	yes	yes	yes
Creekside	no	no	no	7500sf	yes	yes	yes	no
Hillcrest	50m	yes	200'x85' (400)	yes	yes	yes	yes	no
Kerrisdale	30.5m	yes	180'x85' (2500)	no	no	yes	yes	no
Renfrew	25m	yes	no	no	no	yes	yes	no
Sunset	no	no	200'x85' (300)	yes	yes	yes	yes	no
Trout Lake	no	no	200'x85' (250)	no	yes	yes	yes	no
West Vancouver	25m = leisure	yes	separate	5200 sf	yes	yes	yes	no
Gleneagles	no	no	no	4000 sf	no	yes	yes	no

Table 2. *Program Matrix: Case studies of local timber based recreation centers*

iiii.) CURVATURE LIMITATIONS: LAMINATION THICKNESS

Beams have long been manufactured with a small amount of curvature to mitigate deflections. The aim of curving CLT panels is not only to minimize deflections but also provide a more efficient in-plane load transfer path, permitting the structure to behave as a shell. Single curvature CLT panels are (seldom) manufactured in Europe by building-up and curing the laminations over formwork, much like the manufacture of curved Glulams. Based on this similarity, as CSA-O86 contains no guidelines for CLT panels much less curved ones, curvature limits and capacity reduction factors for curved glulam members have been applied to the preliminary design calculations for curved CLT panels [CSA-O86 6.5.6.4]. Table 3 illustrates the relationship between lamina thickness and the smallest allowable radius of curvature (Rc).

Lamination Thickness (mm)	Rmin - Smallest Allowable Radius Measured to Innermost Lam (mm)		Cmax - Tightest Allowable Curvature Measured to Innermost Lam (mm^{-1})		Kx - Residual Stress Factor	
	Tangent Ends	Curved Ends	Tangent Ends	Curved Ends	Tangent Ends	Curved Ends
6	800	800	1.25E-03	1.25E-03	0.888	0.888
10	1200	1400	8.33E-04	7.14E-04	0.861	0.898
13	1800	2200	5.56E-04	4.55E-04	0.896	0.930
16	2300	3000	4.35E-04	3.33E-04	0.903	0.943
19	2800	3800	3.57E-04	2.63E-04	0.908	0.950
25	4600	6200	2.17E-04	1.61E-04	0.941	0.967
29	5600	7300	1.79E-04	1.37E-04	0.946	0.968
32	6300	8500	1.59E-04	1.18E-04	0.948	0.972
35	7400	9500	1.35E-04	1.05E-04	0.955	0.973
38	8400	10800	1.19E-04	9.26E-05	0.959	0.975

Table 3. *Curvature Limitations: Lamination Thickness*

Being an interdisciplinary research project, in addition to calculating the minimal allowable radii, each iteration was examined using visual means to determine the spatial qualities that each radii would yield. The visual component of this enquiry provides a useful reference for any designer who may not be as confident reading engineering tables. The following page contains figures 5 and 6 - an excerpt of the visual investigations corresponding to different entries in table 3. The following visual investigations were also used to determine the bonding agent / wood ratio for both mitred laminations and non-mitred laminations. Earlier ideation led to the idea of mitring the edges of each plank in a panel to ease the process of creating a doubly curved CLT panel. However based on this investigation we found that the glue difference between the mitred and un-mitred panels was negligible. Furthermore, planks which are not mitred saves labour-hours.

iv.) CONNECTION SPACING REQUIREMENTS: NARROW EDGE LENGTHS

Spacing requirements are quite critical for any timber structure. Too narrowly spaced or too near to the edges of the member and the fasteners will tear out like fingers ripping through straw, potentially taking a section from the member with them. Too shallow and they will withdraw rather than hold firm. Choice of connection depends on expected loading: assuming loads do not exceed individual panel capacities, minimum panel width and breadth values have been based upon the largest minimum spacing requirement values for the most demanding configurations of all potential connection types. A survey of CLT connection systems, given in more detail below, showed that self-tapping screw spacing requirements would also provide sufficient room for other connection systems. Resulting width and breadth estimates were made assuming a minimum two-fastener self-tapping-screw connection, with respect to standard Structurlam CLT panel thicknesses as well as the thickness of the fabricated double-curvature prototype. These recommended minimum panel widths and breadths are summarized in Table 1.

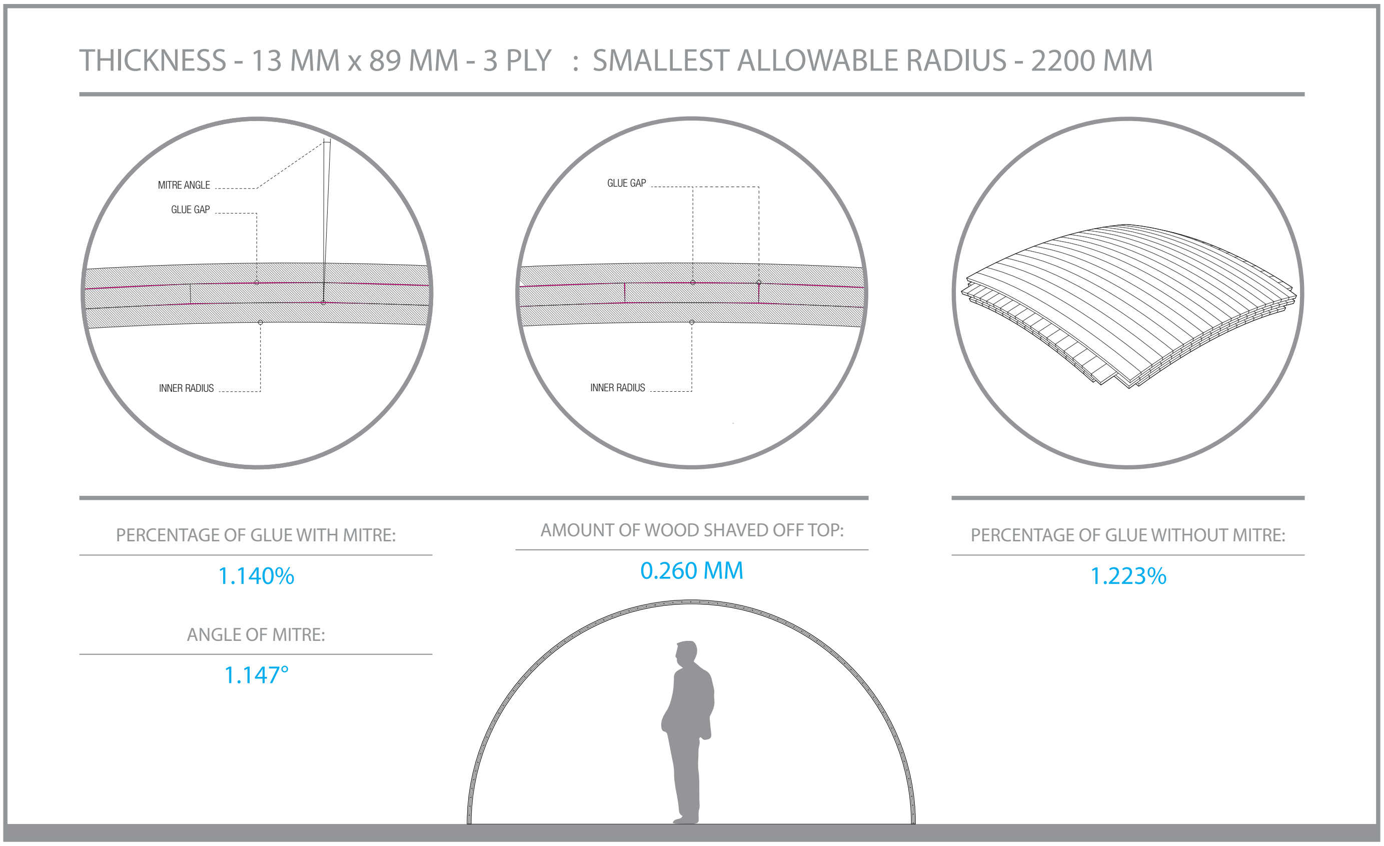


Figure 5. *Curvature Illustration - 13 mm x 89 mm*

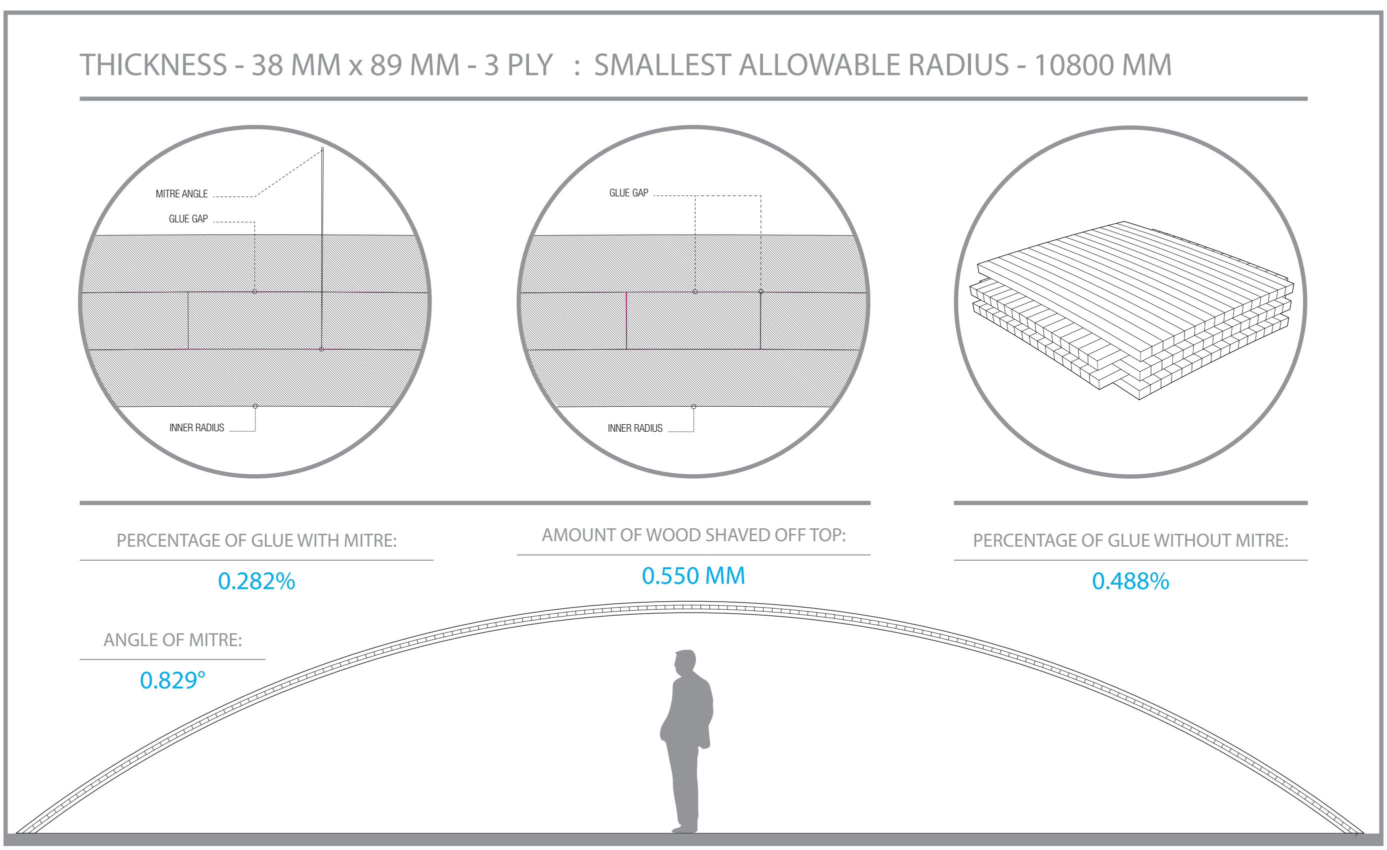


Figure 6. *Curvature Illustration - 38 mm x 89 mm*

V. MANUFACTURING CONSTRAINTS

x. DESIGNING FOR A UBIQUITOUS ‘MACHINE SPACE’

Equally important to structural requirements when considering hi-tech timber systems, are manufacturing constraints. In order for a product to be adopted by industry, it must be able to be produced easily, and with existing technology. As such, we examined the ‘machine space’ of different timber processing machines (as well as a few rapid prototyping machines) in order to determine the design constraints that must be applied when planning joints, connection systems, and panel shaping. The machines that we examined are located either at CAWP or SALA’s building, Lasserre. Our accessibility to these machines and the fairly ubiquitous nature of such technologies such as a CNC machine assure that not only will protoyping at the research phase be streamlined, but also that industry could adopt the outcomes of this research quickly. Table 4 shows the limitations of different machines that have informed our research.

Tool	Location	Min Material	Min Cross Section	Max Material	Min Thickness	Max Thickness	2D Cut	Cost
Hundegger	CAWP	1.25m (L)	50mmx100mm	10 m	na	300mm x 1250mm		$100/hr+ $54/h labour
3-axis CNC	CAWP	Nested Table - no min size if piece secured		48" x 96"	na	3"	1" deep/pass	$70/hr+ $54/hr labour
5-axis CNC	CAWP	Smallest suction cup 2" x 6"; need to have more than 1 suction cup		48"x120"	na	6.75"	1" deep/pass	$70/hr+ $54/hr labour
3-axis CNC	Lasserre			48"x96"	na	10"	3"	$10/hr
Laser	Lasserre	na	na	16"x28"	na	.25"	.25"	$.30/min
Laser	Anex	na	na	16"x28"	na	.25"	.25"	$.30/min
Laser	CAWP	na	na	36"x48"	na	.25"	.25"	na
3D Printer	Lasserre	na		8"x10"x8"	1/8"	na	na	$4/cubic inch

Table 4: *Machining Space*

Figure 7. *Hundegger Milling Machine*

Figure 8. *5-Axis CNC Router*

VI. FORMAL EXPLORATIONS OF STRUCTURE TYPOLOGIES

Each of the three typologies - the doubly curved shell structure, folded plate structure, and lapped plate structure - have been formally investigated to various degrees. Our research, when considering the overall geometry of a speculative construction, focuses on both aesthetics and structure. On a large scale, our investigations are derived from our structural analysis and material research. By setting material properties and structural limits as ‘parameters’ we are able to quickly iterate through many novel forms corresponding to strengths and weaknesses of CLT. These forms are then judged on a basis of formal expression structural feasibility, and construction feasibility. At this point we have examined the pleated structure and doubly curved shell structure on a larger scale.

At the component level we have investigated different geometrical variations of the lapped panel structure and have done in-depth research on the geometry and fabrication of a doubly curved CLT panel.

xi. FOLDED PLATES: FLAT PLATES

The stunning space rendered with the use of folded plate structures has been utilized by architects for decades as seen in projects such as FOA’s Yokohama Pier Port Terminal (2002) or the United States Air Force Academy Cadet Chapel by Skidmore,, Owings and Merril (1962).The folded pleat’s depth provides its resistance to gravity. These surface structures use their global geometry to give strength, maintaining lightness while the depth works for them structurally.

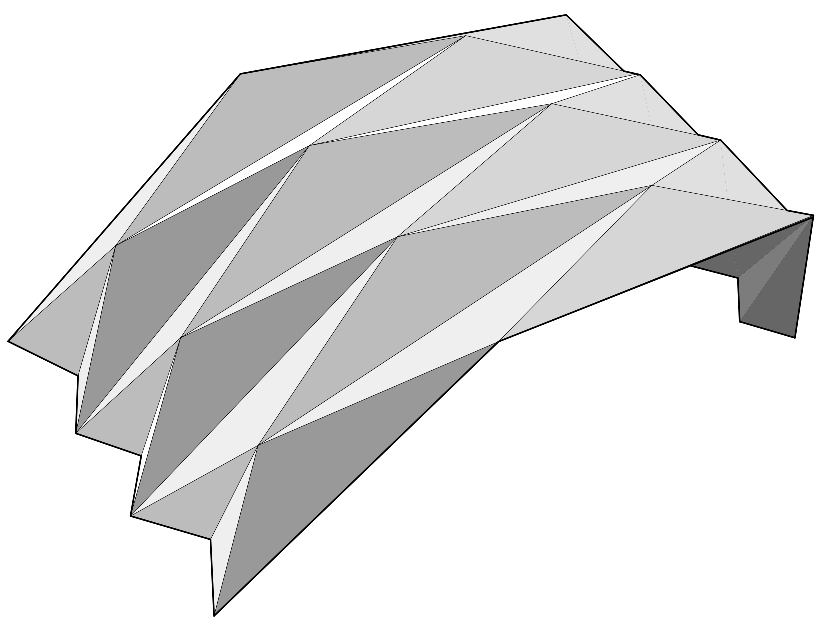
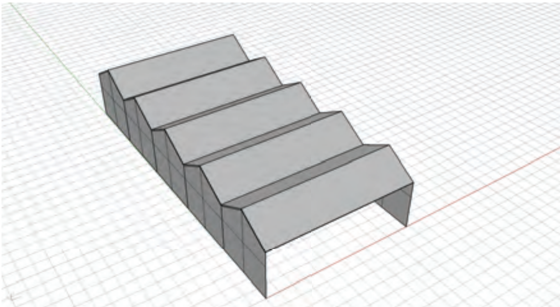
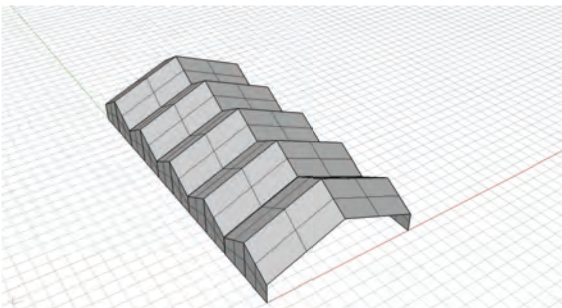


Figure 9. *Typical Folded Plate Structure*

PARALLEL FOLDS - FLAT WALLS





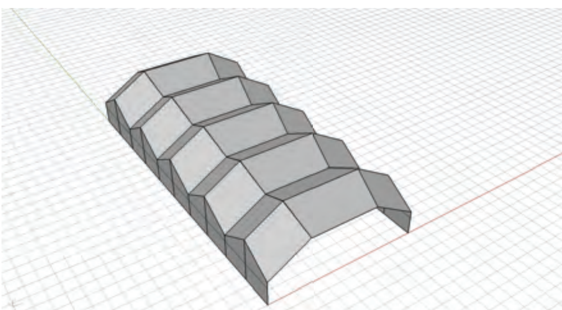
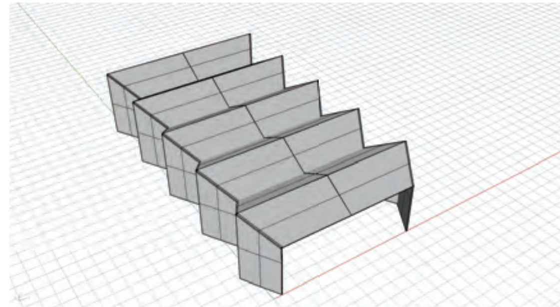


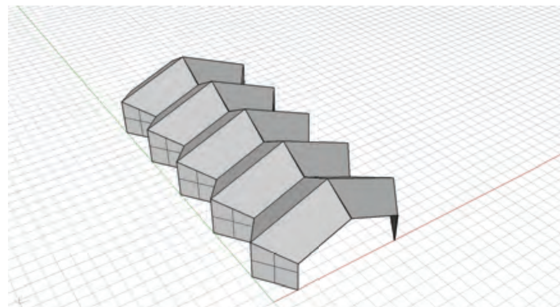
Figure 10. *Parallel Fold Structure Explorations*

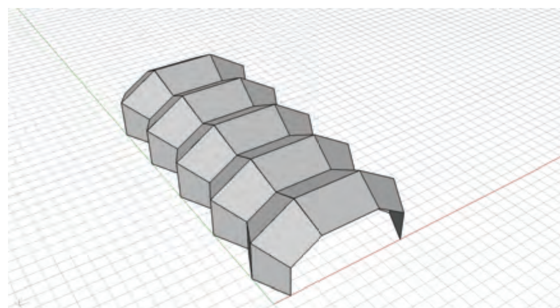
Geometric explorations in folded plate structures were carried out through models that gradually increased in complexity. The explorations were organized into 2 typologies: parallel and diagonal folds. Within each of these categories, flat walled and folded wall options were explored.

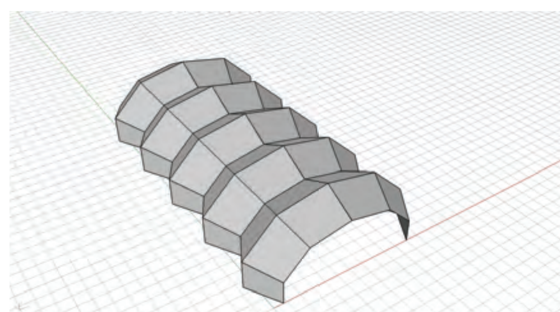
INCREASING COMPLEXITY

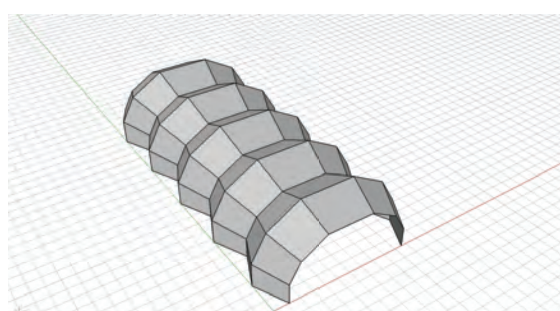
PARALLEL FOLDS - FOLDED WALLS











DIAGONAL FOLDS - FLAT WALLS

DIAGONAL FOLDS - FOLDED WALLS

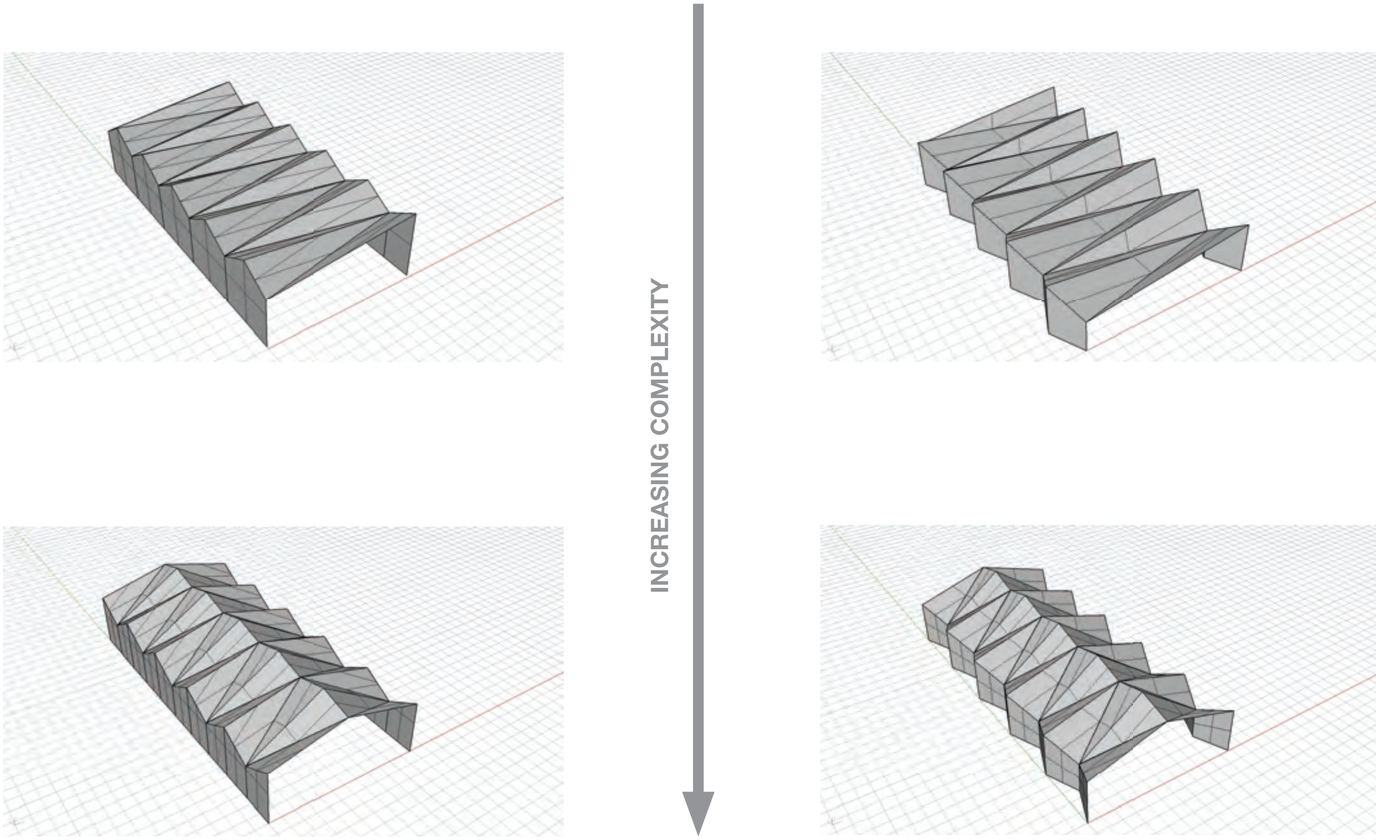


Figure 11. *Diagonal Fold Structure Explorations*

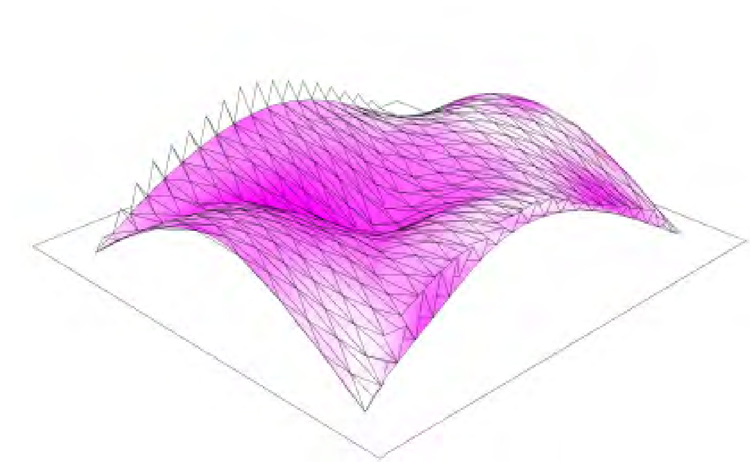
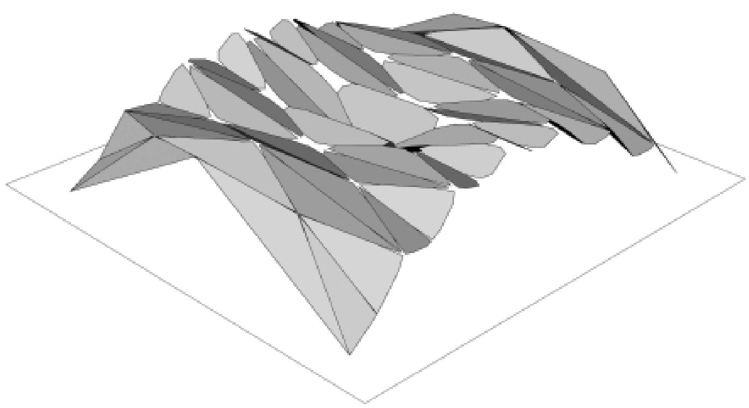


Figure 12. *FEM Analysis of Global Geometry*



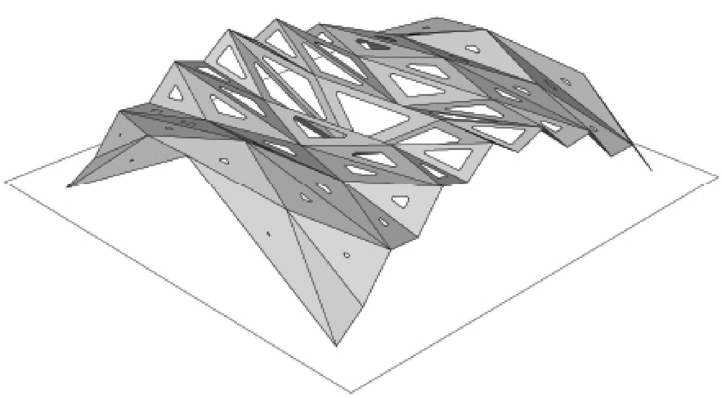


Figure 13. *Exploration of Fenestration in Pleated Structure*

In our study of the global geometry of folded pleat structures in regards to preliminary FEA, we utilized the advanced 3d NURBS modelling package Rhinoceros in combination with the visual programming package Grasshopper. In grasshopper, plug-in Algorithms and parameters are manipulated directly by wiring together components into generative networks. Within the grasshopper interface we have also utilized the Finite Element Analysis (FEA) program Karamba 3d, as well as custom components scripting in the python programming language.

Using this configuration of programs we are able to take a single surface form and create a preliminary structural analysis of the global geometry. We then use a custom algorithm to generate the pleated pattern overtop of the initial global geometry. The algorithm takes into account the structures self weight and deflection and adjust the depths of the pleats accordingly. At this stage the 'resolution' or the amount of pleats generated in both the x and y directions of the initial global geometry can be reduced or increased. (Figure 12)

Following the initial 'pleating' of the global geometry the designer is able to experiment with various fenestration patterns. Again the algorithms used in this process take into account the structural analysis of the global geometry and generate a patterns of openings based on local conditions. We are currently exploring both openings in the centres of all panels and openings created at the corners of the panels. (Figure 13)

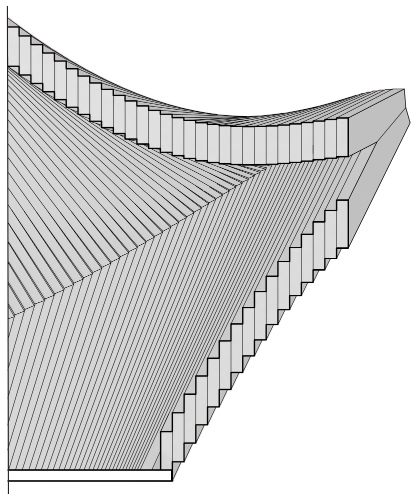


Figure 14. *Lapped Panel Structure*

xii. OVERLAPPING PLATES: SINGLE CURVATURE

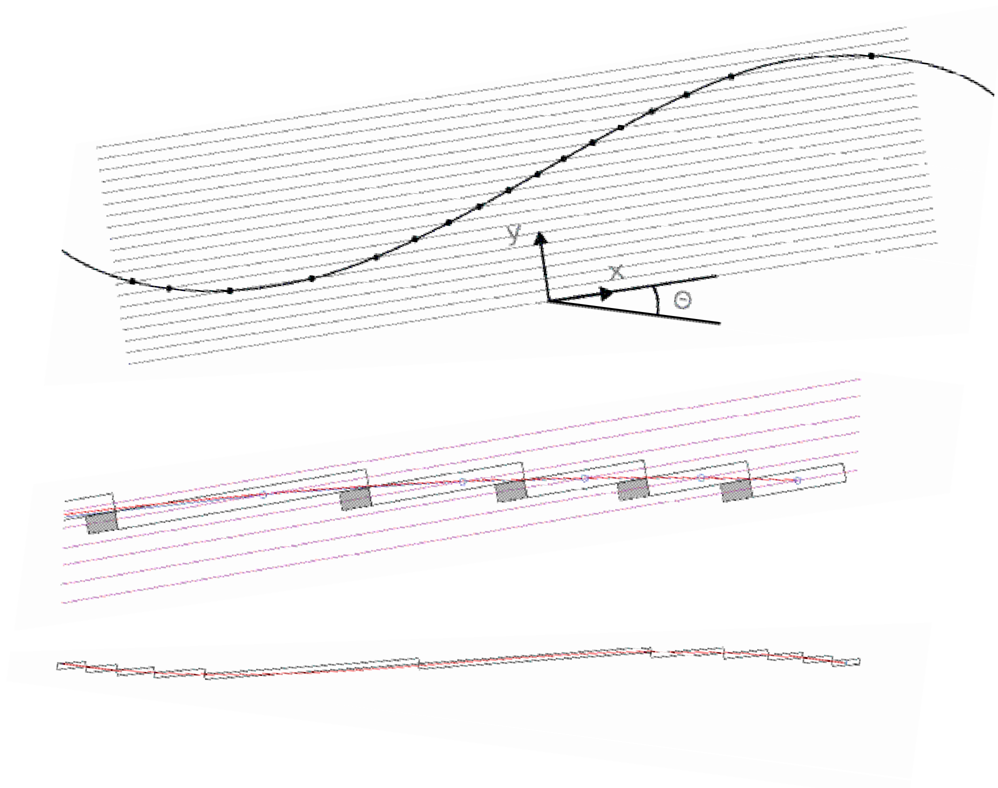
In our formal explorations with doubly- curved CLT structures, we have investigated both the global geometry level and the component level in order to reveal wood's potential as a material capable of creating complex curved forms. In combination with our explorations of subtractive processes, we are exploring a process in which panels are CNC milled then lapped over one another to create more complex forms. We have developed a set of tools within the Rhino 3D interface that allows us to panelSize doubly-curved surfaces, allowing for parametric variation of sizes, depths, lamination thicknesses, and more.

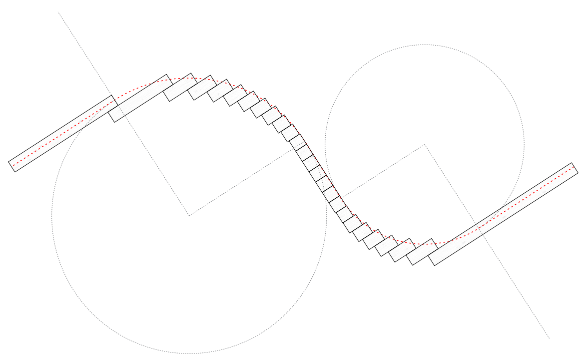
The first of these parameters is the directrix, or the guiding line which extends throughout a series of panels. (Figure 15) We made the first division of explorations based on whether this directrix was straight or curved. In order to start with geometrical potentialities rather than material limitations, we began our exploration with abstracted ruled surfaces. This type of surface was chosen because its potentially complex organic forms can be derived by sectional straight lines. (Figure 14)

From this investigation we further explored simple geometrical transformations that could be made around the directrix. For both the straight and curved directrix we explored the transformations: uniform tilting, flaring, and flaring with tilting. (Figure 17)

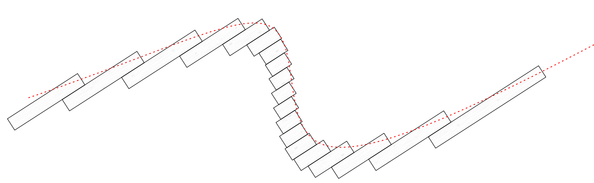
Future investigations will center around applying these different iterations onto complex and curved global geometries.

CONTOURING: APPROXIMATION OF PLANAR CURVATURE





straight lines;
curves of constant radii



curves of constantly-varying radii

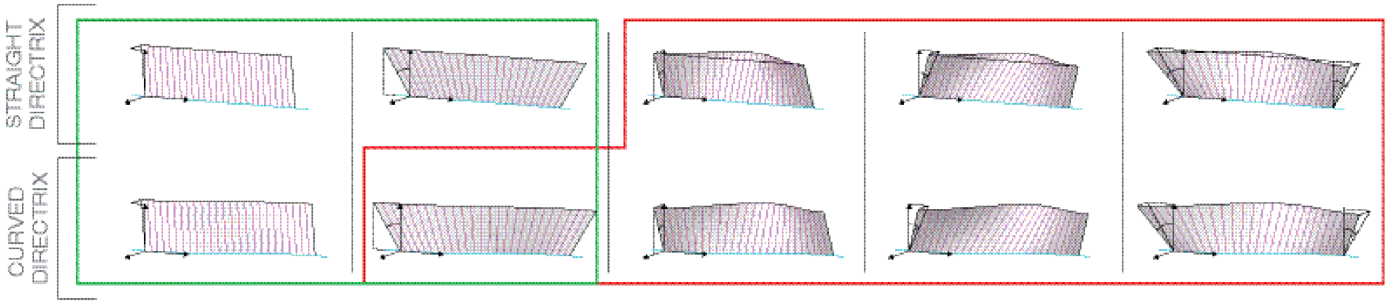


__Figure 16.__ Ruled Surfaces: Straight and Curved Directrix

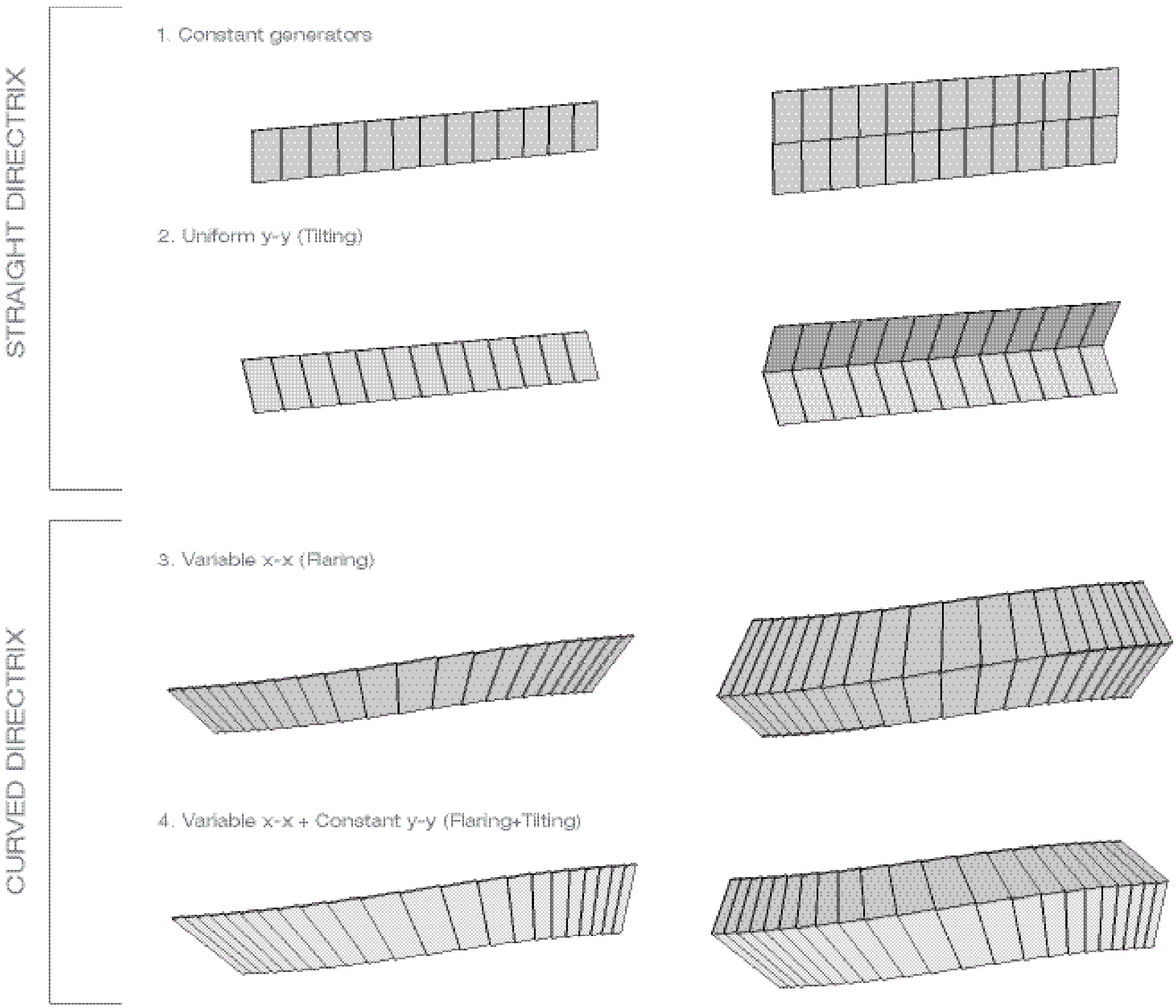


__Figure 17.__ Lapped Panels Applied to Straight and Curved Directrix

CONTOURING IN THREE DIMENSIONS:
SINGLE AND DOUBLE CURVATURE WITH FLAT PANELS

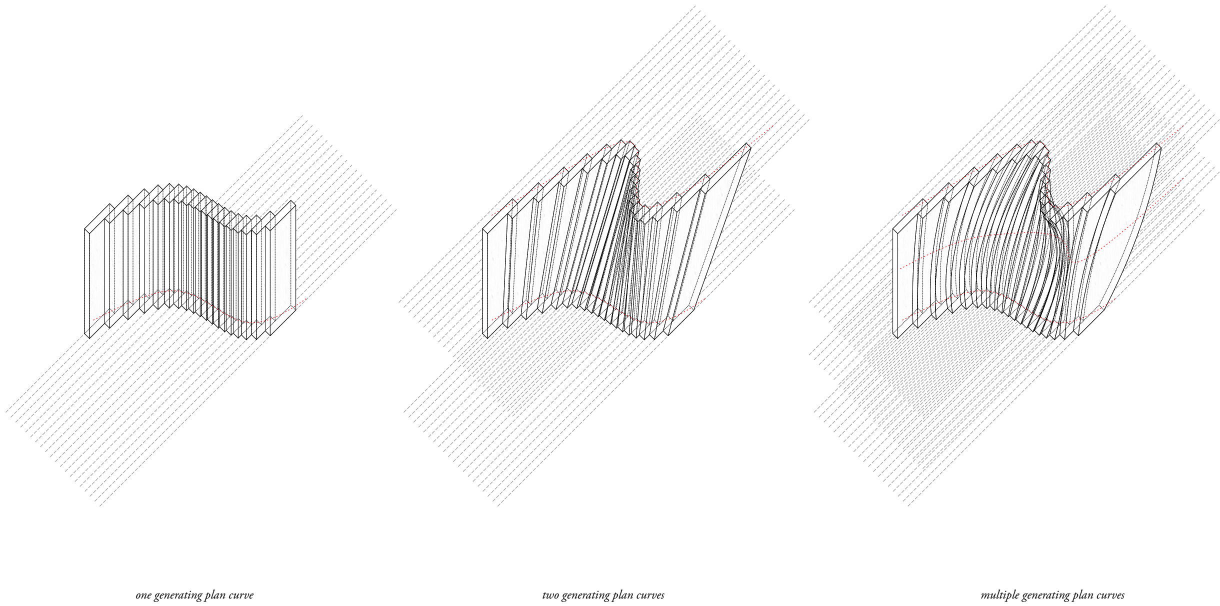


Figure 18. *Render of a lapped CLT structure*

xiii. CONTINUOUS SHELLS: DOUBLE CURVATURE

Surface structures have fascinated us since the Renaissance with domes, and vaults providing the first examples and more recently with more complex forms such as Gaudi's Sagrada Familia, Saarinen's TWA Terminal, and Toyo Ito's Funeral Hall. One can speculate on what draws us to these forms - perhaps their lightness, their curved forms, their complex interaction with light or the intuitive flow of force which is expressed within their form. The hyper-efficiency of the structures provide an architectural form which seems to defy gravity.

In our formal explorations with doubly curved CLT structures we have done investigations into both the global geometry level and the component level in order to reveal wood's potential as a material capable of creating seamless curved forms.

Considering global geometry we have designed a set of tools using Rhino 3D, Grasshopper, and the physics simulation Grasshopper plugin Kangaroo that allow us to quickly iterate through various funicular forms. The high degree of flexibility in this design process allows us to create novel forms that can be easily modified to suit the needs of the doubly curved CLT panels that we are currently developing. (Figure 19)

At the component level, in combination with our structural analysis of wood bending we are exploring a process inspired by barrel making in order to generate doubly curved CLT panels. We have developed a set of tools within the Rhino 3D interface which allows us to generate panels of varying sizes, depths, and laminations. (Figure 20)

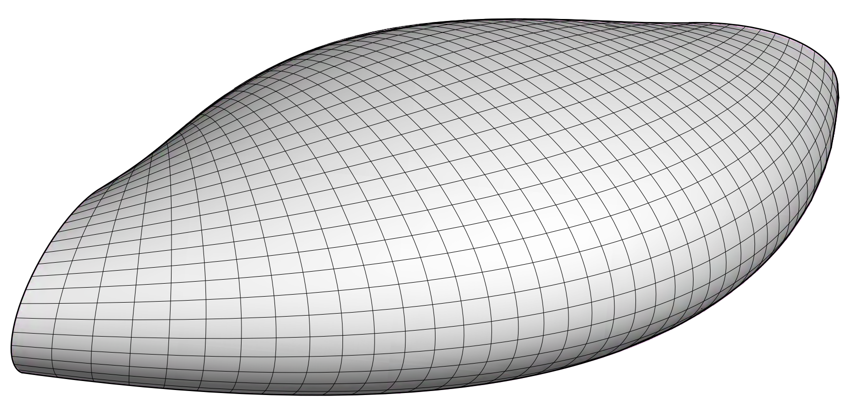
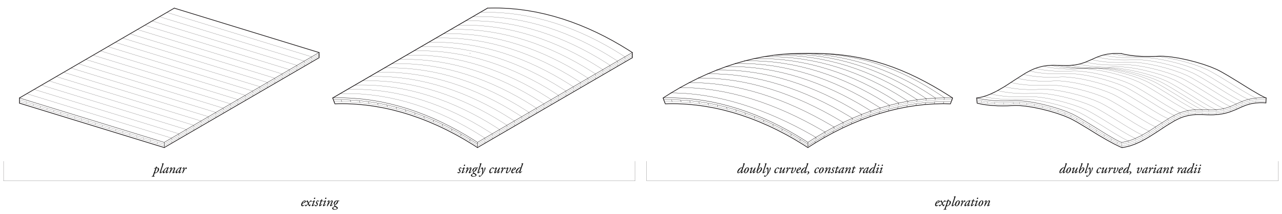
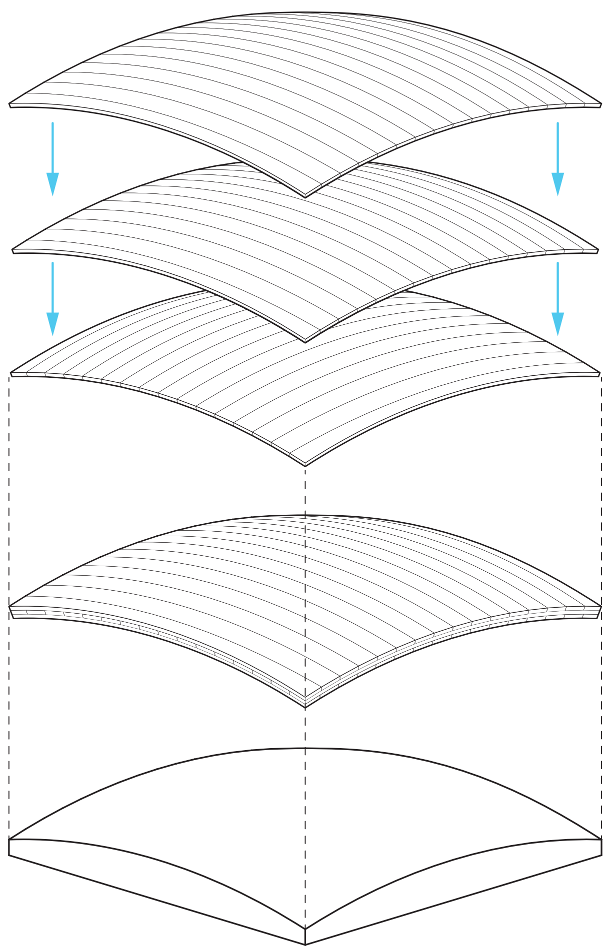


Figure 19. *Speculative Doubly-Curved CLT Structure*



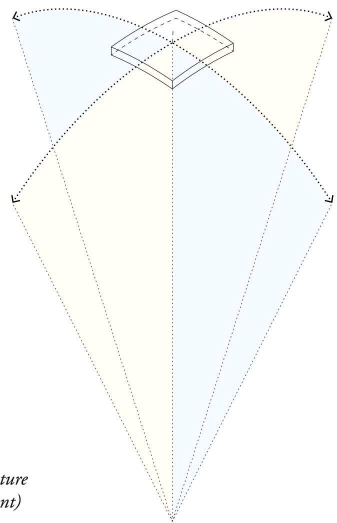
CLT panels: current and future



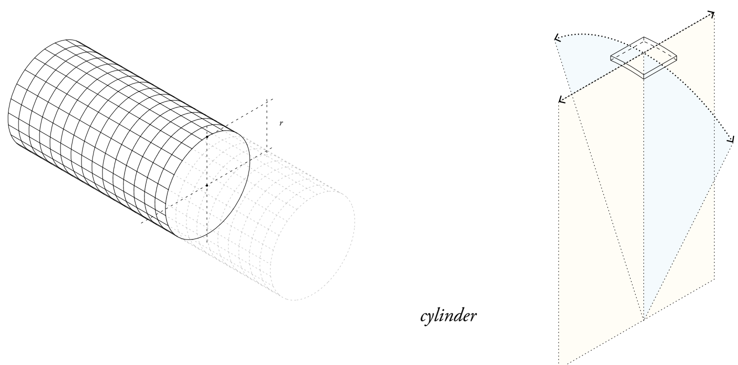
doubly curved CLT panel strategy

Figure 20. *Parametrically Generated*
Doubly Curved *CLT Panel*

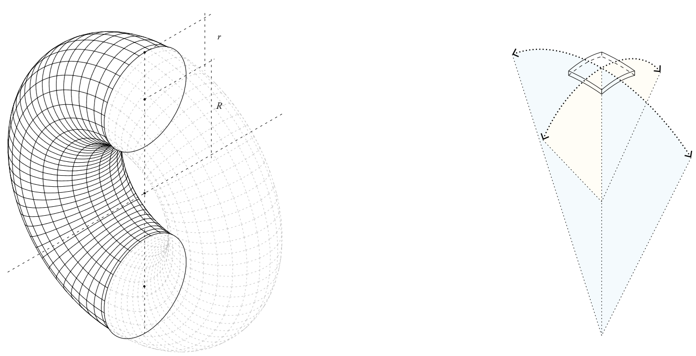
GEOMETRIC PROPERTIES



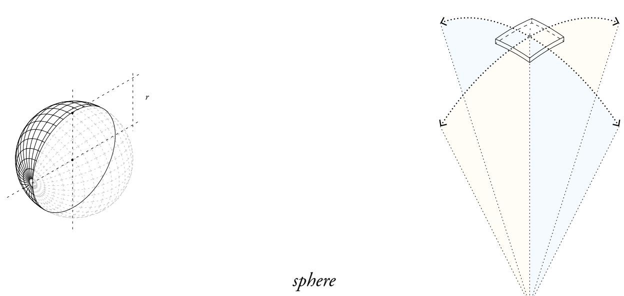
isoparametric curvature
(curvature at a point)



cylinder



torus

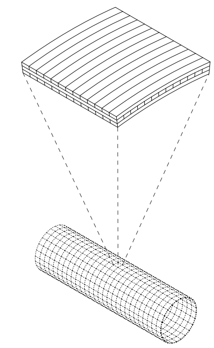


sphere

PARAMETRICITY OF CURVED S

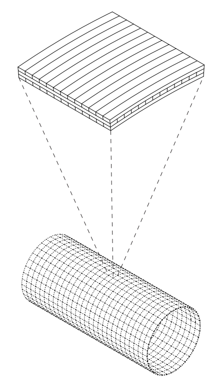
R = ∞
(cylinder, single curvature)

r = 14 ft.



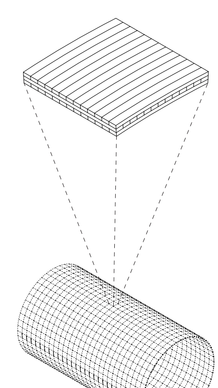
14, ∞

r = 21 ft.



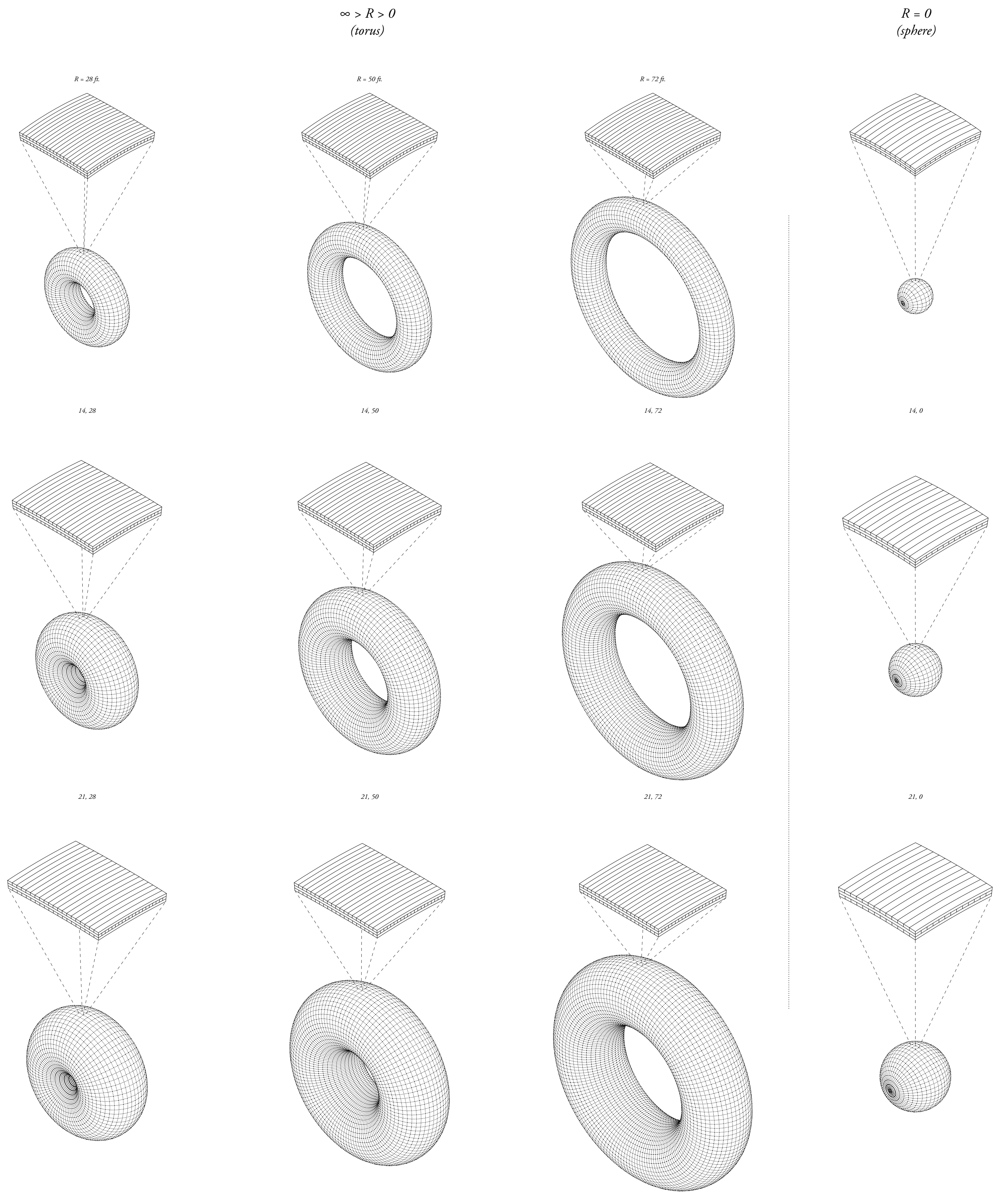
21, ∞

r = 28 ft.



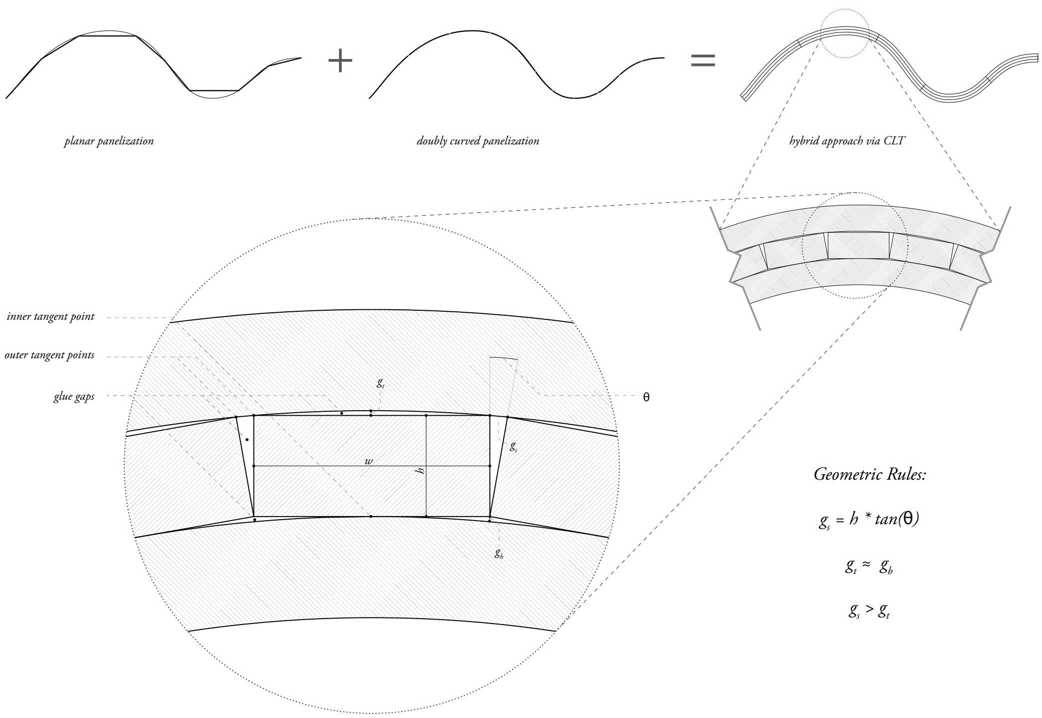
28, ∞

URFACES



$\infty > R > 0$
(torus)
$R = 0$
(sphere)
R = 28 ft.
R = 50 ft.
R = 72 ft.
14, 28
14, 50
14, 72
14, 0
21, 28
21, 50
21, 72
21, 0
28, 28
28, 50
28, 72
28, 0

HYBRID RATIONALIZATION VIA LAMINATIONS



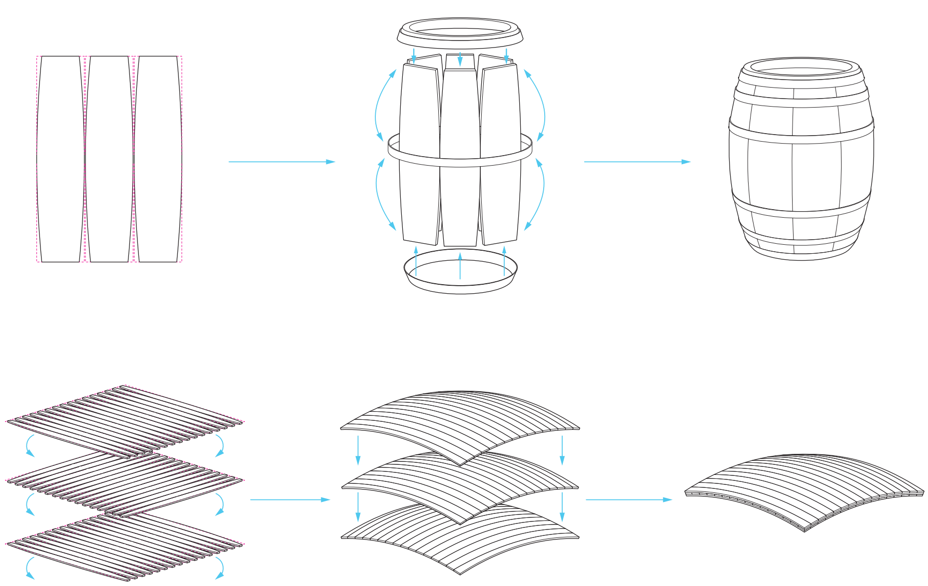
Geometric Rules:

$g_s = h * tan(\theta)$

$g_t \approx g_b$

$g_s > g_t$

PRECEDENT: BARREL-MAKING

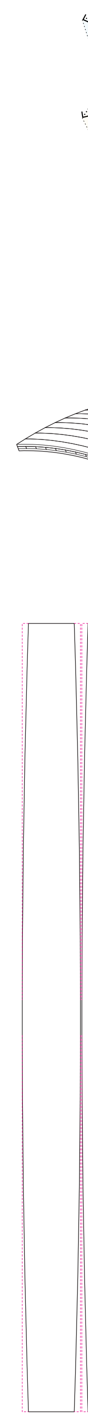


PANEL FORM / LAMIN

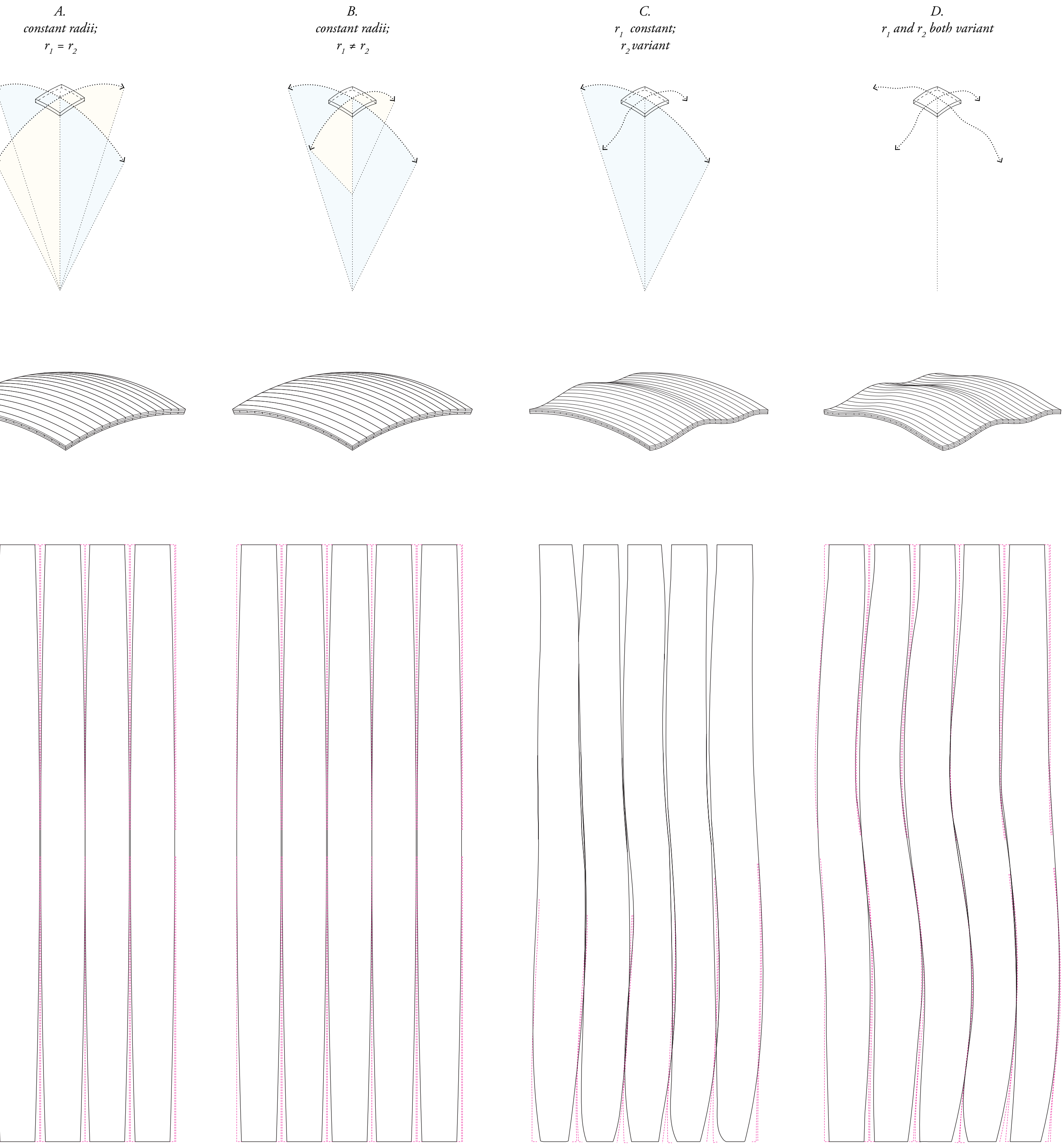
curvature type

panel form

lamination form



NATION FORM RELATIONSHIP

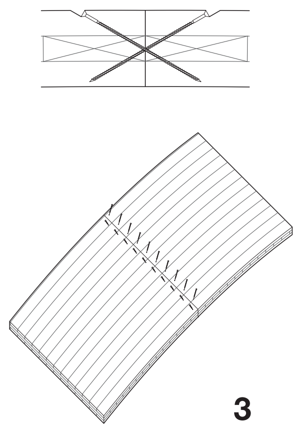


VII. PROPOSED CONNECTIONS

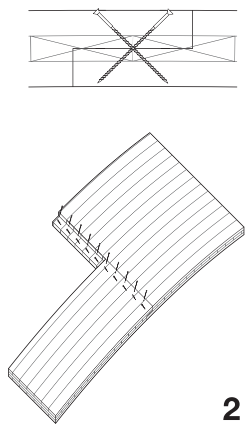
INDUSTRY STANDARD

INCREASING COMPLEXITY

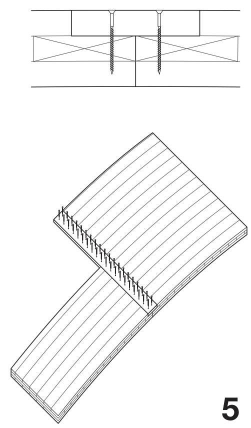
CONTINUOUS PLATES



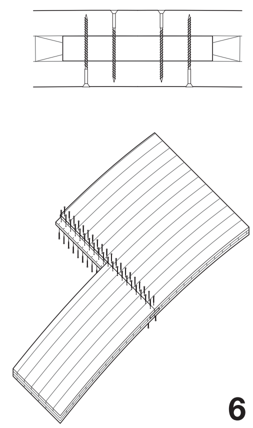
3



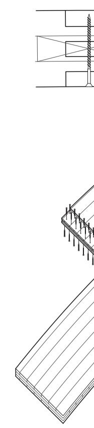
2



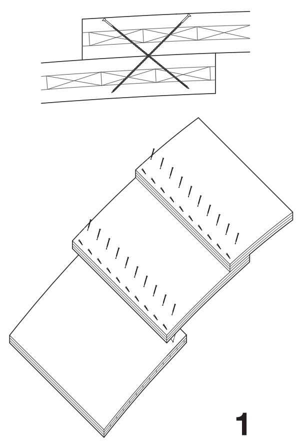
5



6



LAPPED PLATES

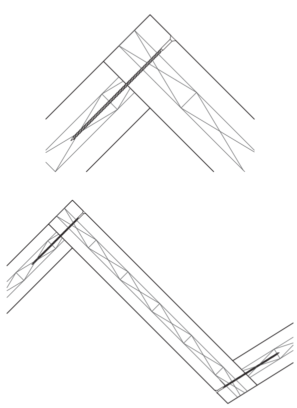


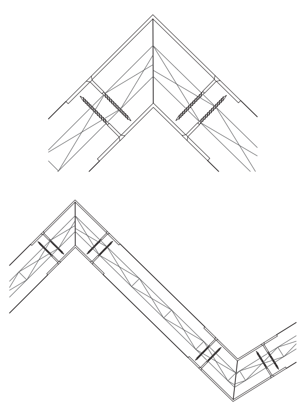
1

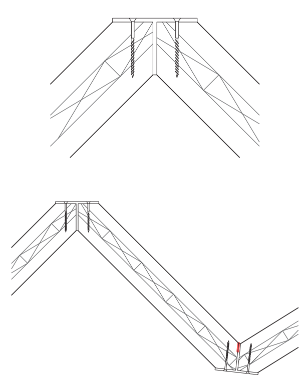
Joint Type	Lapped	Half-Lapped	Butted	STS-Rei Dovetail C
Number Assignment	1	2	3	4

****NUMBERS ARE*** *ASSIGNED IN THE ORDER THAT THEY ARE DESCRIBED IN THE FOLLOWING S*

FOLDED PLATES

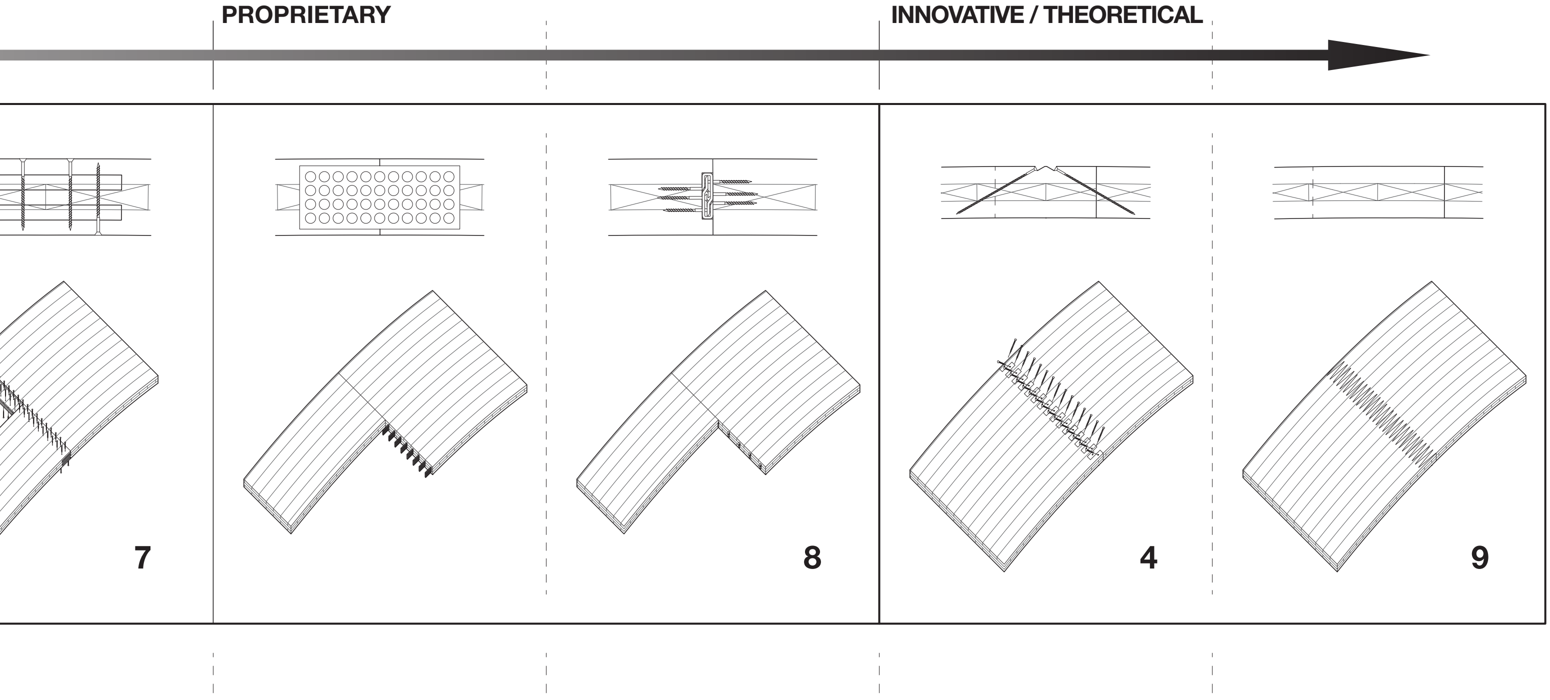






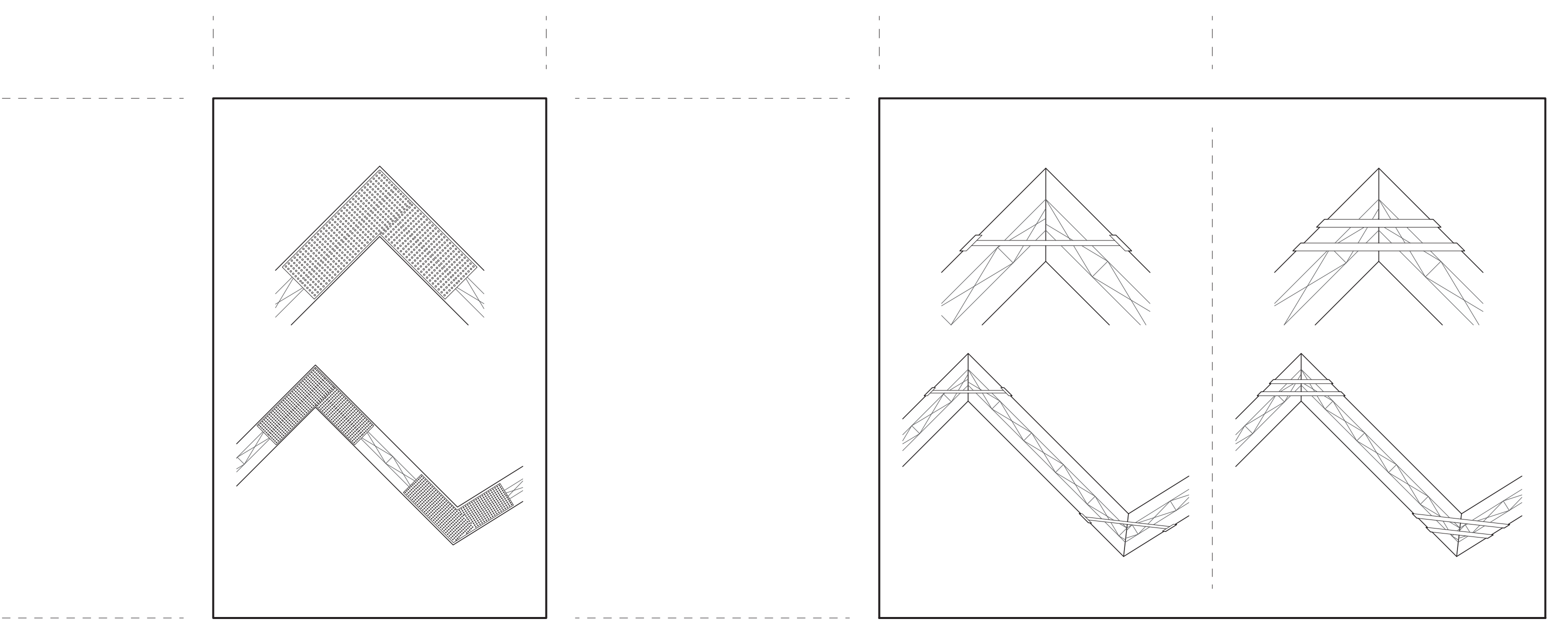
10

Table 5: *Connections organized by Typology and Complexity*



nforced onnection	Top Spline	Interior Spline	Tongue-and-Groove	KNAPP WALCO V60	Adhesively-Bonded Finger Joint	Steel Plate for a 30° Corner
4	5	6	7	8	9	10

SECTION



xiv. INTRODUCTION

Connection design controls how and where loads are transferred from one structural element to another. Usually this is a process which begins by adjusting external load values to the dimensions of a predetermined form. Design loads are estimated for temporary structures, as follows :

Loads	Curved Prototype	Structurlam Panel
Dead	5.2 kN/m3 for Douglas Fir; 0.5 kPa for roofing	4.4 kN/m3 for SPF 0.5 kPa for roofing
Live	1.0 kPa	1.9 kPa
Snow	1.0 kPa	1.0 kPa

Table 6

In a parametric design study, explicit geometric values or member configurations are not available. It is not unreasonable, however, to expect plates to occasionally form roof or wall-like assemblies. Therefore, though the final structure is expected to have more complex geometry and excised apertures, a simplified configuration can be considered for preliminary connection designs. Two panels were assumed to be horizontally oriented between simple supports. Therefore, for the two panel types under consideration, the connection design data is as follows:

Panel Type	Prototype Double Curvature Panel	Standard Structurlam Panel
Thickness	13mm layers; 39mm total	32mm, 35mm, 32mm layers; 99mm total
Length x Breadth	1,200mm x 1,200mm	3,000mm x 3,000 mm
Wood Species and Density	Douglas Fir, 5.2 kN/m3	SPF, 4.4 kN/m3
Uniformly Distributed Load, ω	2.733 kN/m	13.564 kN/m
End Reactions, V	3.28 kN	40.69 kN

Table 7

Similar research seeking to achieve free-form geometries with timber panels has been conducted very recently or is concurrent with our own work[1]

A brief survey of connection design methods identifies common strategies and highlights where fabrication and assembly considerations could be addressed further. In all cases the designers seek to achieve free-form geometry with planar timber panels; their connection design methods can be broken into two components. First, how panel edges are milled into mating surfaces—for instance, butted or dovetail-edged. Secondly, how individual panels are secured, either with mechanical fasteners or adhesively-bonded glued-in plates.

1. Haasis, 2008; Weinand, 2009; LaMagna et al, 2012; Fischer et.al 2012; Tas, 2013; Robeller et al, 2014; Schimek et al. 2014

Institution	Project	Panels Edges	Connections	Sources
IBOIS, EFPL Lausanne	Origami Folded CLT	Butting	Self-tapping wood screws (pavilion) HSK plates (temporary chapel)	Haasis, 2008 Weinand, 2009
	Curve-Folded CLT	Dovetail jointed	Self-tapping wood screws	Tas, 2013 Robeller et al, 2014
IDTKE, Stuttgart	Biomimetic Structures	Dovetail jointed	Self-tapping wood screws	LaMagna et al, 2012
TU Graz	“Sewn” CLT	Butting	Glued-in plywood plates	Fischer et.al 2012 Schimek et al. 2014

Table 8

Importantly, all previous studies conclude that for free-form geometries, fully rigid connections between panels are necessary to provide the required performance. Rigid connections at panel edges redistribute bending and load demands, minimize deflections and allow for greater spans and thinner panel sections. [1] The ability to devise fully rigid panel edge connections or assemblies has therefore been given thorough consideration in this study.

Given these examples and our own design constraints, the broad list of potential connection systems described in the initial preliminary report has been reduced. The following table lists two generic connector types. Each branches out into subtypes and other smaller design variations, which will be explained in more detail:

Connector	Self-Tapping Screws				Adhesive	
Type	Screws Only		With KNAPP Hangers		Finger Joints	Tongue-and-Groove
	90°	45°	Walco V60	Ricon S 80/40		
Application	Half-Lapped Lapped Top Spline Tongue-and-Groove	Butted Half Lapped Lapped Alternating Fingers	Dropped-in Panels	Slotted-in Panels or Modular Panel Assemblies	Co-planar Panel assemblies “Folded” Panel Assemblies	Co-planar Panel Assemblies

Table 9

1. Haasis, 2008; LaMagna, 2012; Tas, 2013

xv. ASSEMBLIES WITH SELF-TAPPING WOOD SCREWS

Direct Panel-to-Panel Screwed Assemblies:

Self-tapping screws (STS) are the industry standard connector in Europe for CLT panel assemblies [1]. These screws are made from high capacity steel, need no pre-drilling, and are easy install. Properly designed STS connections are highly efficient, practical, and easy to hide by countersinking screw heads into the panels and filling the holes with wood inserts. Though not a rigid connection and designed as simple supports, pairs of crossed screws are used to provide moment resistance. Only the threaded section embedded in the main member, termed the effective length (lef), provides withdrawal resistance for the connection. These connections function best when screws are loaded in withdrawal and inserted at an angle to the grain direction of the outer layer to maximize lef; 90° insertions may be favourable for ease of assembly.

Eurocode 1995, in conjunction with the ETA and the CCMC approval for Würth ASSY STS, approaches the design of STS by considering screw lateral and axial capacities under shear and tensile loads, respectively. Shear demand is calculated according to Johansson yield equations, while screws loaded predominantly in tensions or compression are designed according to their withdrawal resistance.

The thickness of the CLT panel limits the maximum allowable diameter of the fastener, upon which related spacing requirements and minimum panel breadths are based. According to the CCMC approval for Würth ASSY STS, the maximum screw diameter is 1/10th of the panel thickness. Additionally, the total length of the screw must not allow it to protrude from the panel assembly. Providing a minimum 6d (6 times the screw diameter) edge distance “margin” at the perimeter of all STS connections accommodates any of the proposed the connection configurations, whether loaded in tension, compression, or bending. Arrays of screws, either perpendicular or angled, must have a separation of at least 4d, though the shafts in a pair of crossed screws may be as close as 2d.

1. Mohammed, 2011

Full calculations for panel-to-panel assemblies with Würth ASSY VG fully threaded self-tapping screws are in the appendix, but are summarized here by joint and panel type:

Joint Type	39 mm Prototype Panels	99 mm Structurlam Panels
Lapped	(4) φ3 mm x 50 mm STS (2 pairs) inserted at 90° spaced at 400 mm o. c. Or (4) φ3 mm x 70 mm STS (2 pairs) inserted at 45° spaced at 400 mm o. c.	(8) φ 6 mm x 180 mm STS (4 pairs) inserted at 90° spaced at 600 mm o. c. Or (6) φ 6 mm x 260 mm STS (3 pairs) inserted at 45° spaced at 750 mm o. c.
Half-Lapped	(5) φ3 mm x 30 mm STS inserted at 90° spaced at 300 mm o. c. Or (4) φ3 mm x 50 mm STS (2 pairs) inserted at 45° spaced at 400 mm o. c.	(11) φ6 mm x 90 mm STS inserted at 90° spaced at 250 mm o. c. Or (16) φ5 mm x 120 mm STS (8 pairs) inserted at 45° spaced at 300 mm o. c.
Butted	(4) φ3 mm x 50 mm STS (2 pairs) inserted at 45° spaced at 400 mm o. c.	(16) φ5 mm x 120 mm STS (8 pairs) inserted at 45° spaced at 300 mm o. c.
Top Spline	(2) φ3 mm x 35 mm STS inserted at 90° spaced at 400 mm o. c.	(3) φ6 mm x 90 mm Würth ASSY self-tapping screws inserted at 90° spaced at 750 mm o. c.
Interior Spline	(4) φ3 mm x 50 mm STS (2 pairs) inserted at 45° spaced at 400 mm o. c.	(12) φ6 mm x 90 mm STS (6 pairs) inserted at 90° spaced at 23 0 mm o. c.
Tongue-and-Groove	(5) φ3 mm x 35 mm STS inserted at 90° spaced at 200 mm o. c.	(11) φ6 mm x 90 mm STS inserted at 90° spaced at 250 mm o. c.
Steel Plate for a 30° Corner	(4) φ3 mm x 30 mm STS (2 pairs) inserted normal to plate top spaced at 400 mm o. c.	(12) φ6 mm x 90 mm STS (6 pairs) inserted normal to plate top spaced at 230 mm o. c.

Table 10

KNAPP Connectors:

Large scale folded plate and tessellated plate structures benefit from a flexible and simple method of assembly. KNAPP connectors are interlocking steel bolts and hangers which allow timber frame elements to be dropped or slid into place during construction, or removed easily if desired. These clips can also be fully hidden by countersinking the stirrups into pre-milled slots in the member surfaces. Each clip is fastened with STS and has a pronged, steel dovetail to interlock with a larger screw which protrudes from the dependent member. A wide array of clip types, sizes, and capacities are available with different variations upon the general mechanism described above. Most are too large for the panels under consideration in this study, but would be applicable to large-scale projects. KNAPP Walco V60 clips require only 80mm of timber and are therefore suitable for folded plate structures assembled from standard three-ply 99mm thick Structurlam CLT panels. These clips could be included in the prefabrication process, attached to either individual panels or to the longitudinal edges of multi-panel assemblies.

99 mm Structurlam Panel
Use (14) WALCO V60 connectors Spaced at 200mm o. c.

Table 11

xvi. ADHESIVELY BONDED JOINTS

On Adhesives in Timber Connections

True shell and plate behavior is unattainable when geometric or material discontinuities, such as corners or denser metal connectors, are introduced. These discontinuities produce local stress concentrations and subsequently initiate failure mechanisms [1]. Orthotropic materials, such as timber, are prone to failures resulting from perpendicular to grain (out of plane) compressive or tensile stresses, parallel to grain shear stresses, or a combination of both [2] . Mechanical fasteners not only induce such stresses but also reduce the cross section of the timber member and damage local wood fibers during insertion.

In contrast, adhesively-bonded connections do not weaken the members themselves and distribute the load over the entire bonded surface, thereby minimizing stress concentrations. These connections also exhibit favorable behavior in reversed loading and are far stiffer than mechanical connections [3] , and can be used to bind multiple adherents with different material properties [4] . As such the use of adhesive in conjunction with more conventional mechanical connection systems to improve their performance, as well as adhesively-bonded glued-in rods or perforated metal plates to form timber moment connections has gained popularity [5]. Owing to the complexity of designing for multiple materials and adhesives, these types of connections have not garnered wider acceptance due to lack of universal agreement on design guidelines [6].

---

1. Tas 2013
2. Lehmann et. al. 2013
3. Lehmann et al 2013
4. Custodio 2009
5. Chans, et. al. 2008
6. Vrazel & Seller, 2004; Chans et al, 2008; Custodio, 2009; Lehmann et al 2013

It is interesting to note that wood-to-wood adhesively bonded connections are fully rigid. This ability provides the basis for the production of mass engineered timber elements. Not only are laminations bonded with adhesive on their surfaces, but individual laths are formed into continuous strips by joining their ends with adhesively-bonded finger joints [7]. Purely adhesively-bonded connections would bypass the necessity for mechanical fasteners and their associated negative traits altogether. Assuming uniform geometry between plates, theoretically an adhesively-bonded finger joint connection could achieve shell or plate behavior.

In the survey of similar research projects described earlier, only the "Sewn" CLT project [8] applied adhesive to the joints between CLT edges. As of the writing of this report only architectural papers for the "Sewn" CLT project have been published and though promising, the structural behavior and performance of the proposed system cannot be commented on, but presumably the decision to use glued-in plywood plates was based upon the advantages of adhesive connections described above. Unglued dovetail joints were used in the other project, but transfer only in-plane loads. Additional STS were required for partial transfer of bending moment between panel elements. A glued dovetail joint is still inferior to a finger joint because its rectangular profile is a more sudden change in the edge geometry and provides less bonding surface.

Two panel edge profiles have been considered as candidates for adhesively bonded panel connection assemblies. One applies the finger joint used to create continuous laths to whole CLT panels, while the other considers extending off-setting individual CLT layers to create continuous tongue-and-groove edge joints.

Finger Joints

The tapering profile of finger joints provides a greater effective adhesive bond area than dovetail joints and a smoother change in geometry [9]. These finger joints can have up to 75% of the strength of clear wood [10], and given advances in machining and fabrication technology, applying finger joints on a larger scale is a feasible and attractive connection option. The geometry of a finger joint profile can be described with interrelated parameters, illustrated as follows:

t	**tip of finger**
L	**length of finger**
l	**length of finger slope**
P	**pitch (base width) of finger**
tan (Θ) = L/P	**slope of finger**

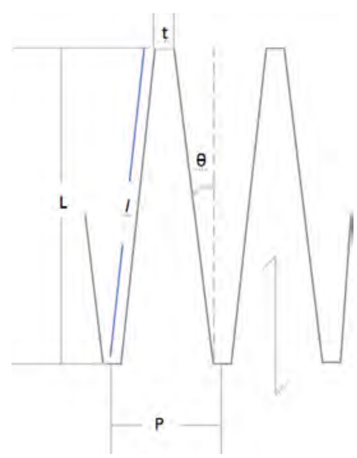


Figure 21. *Finger Joint Geometry*
(after Jokerst 1982)

7. Chans, et.al. 2008
8. Fischer et al 2012; Schimek et al, 2014
9. Jokest 1982
10. Vrazel, Sellers Jr., 2004

The strength of an adhesively-bonded finger joint, assuming high shear strength performance on the part of the adhesive, depends on the strength in shear parallel to the grain of the pieces being joined. This strength is normally one tenth or less of the tensile strength. Therefore effective glue joint area disregards the area of the tips and must be at least 10 times the net section of the joint to develop a significant proportion of the tensile strength of the wood. The resistance to the applied stresses is provided by the net section itself. Additionally, finger tips as small as practically possible not only contribute to a larger effective glue joint area but also maximize the net section.

The pitch (spacing of fingers) must be large enough to minimize interaction between stress concentrations that occur at the tips, but not so large that the number of fingers, and therefore the available effective glued area, is insufficient to develop sufficient stress resistance. This stress development depends on sloping joint area/ratio of length to pitch and, if assuming a unit area, reaches a maximum at $L/P > 4$. However, minimizing the slope and the tip while maximizing the net section will increase the joint strength but at a decreasing rate of return.[1]

Finger joints may be designed according to a desired number of fingers or finger length, so long as the glued finger area will be at least 10 times as large as the net section area. Here, a tip width of 5mm and a finger slope of 5°. Thereafter finger length and number of fingers can be calculated, but may be adjusted to meet a convenient whole number of fingers.

	39 mm Prototype	**99 mm Structurlam**
Edge Length	1215 mm (curved)	3000 mm (straight)
Finger Length	75 mm	100 mm
Number of Fingers	81	150

Table 12

1. Jokerst, 1981, 1982

Tongue-and-Groove Joints

Like dovetail joints, tongue and groove joints have similar rectangular profiles and so the same deficiencies. Such joints would not require special edge cuts, however, and could be produced simply by offsetting the laths in a panel to produce alternating gaps and protruding tenons along the edges. Several panels produced in this way could socket into one another like puzzle pieces. They may be secured by self-tapping-screws as described previously, or they could be adhesively bonded. As with the finger joints, the tenon length is determined by the necessity to provide 10 times as much glued area as net section area and then rounded up to the nearest 5 mm.

	39 mm Prototype	99 mm Structurlam
Edge Length	1215 mm (curved)	3000 mm (straight)
Number of Laths	16	32
Number of Tenons	8	16
Finger Length	115 mm	250 mm

Table 13

VIII. INTEGRATION OF DIGITAL ARCHITECTURAL MODELS WITH FINITE ELEMENT ANALYSIS SOFTWARE

Since the division of role of the classical architect into the contemporary “architect” and “engineer” communication confusion and disconnect between the two sibling professions has contributed to no small amount of discord between the two. However, digital design and computational tools now enable both to perform at levels that were previously impossible. The most celebrated contemporary buildings and structures are the work of close collaboration between architects and engineers. To encourage such collaboration it is necessary to adopt modelling and analysis software that can be knitted together and implemented in a Building Information Modelling (BIM) design schema.

Your generic architecture firm does its modelling and drafting in a CAD program: such as AutoCAD and SketchUp. Upon receiving the plans from the architect, the engineer will import them into analysis software: SAP2000 is one example. Should one professional decide to alter a column position or introduce an aperture, the change is not automatically adopted across all design files. Model conflicts and confusion ensue.

Disconnect and chaos between digital models and analyses is unnecessary. Architectural and structural model integration, one of the objectives of this study, would not only accelerate the design process but also enable greater degrees of innovation.

Rhinoceros (Rhino for short) is a 3D NURBS Modelling software. Lines and surfaces are based on numerical algorithms. The Rhino plug-in Grasshopper provides a visual programming language, bypassing the drafting user interface altogether. Algorithms and parameters are manipulation directly by wiring together components into generative networks. Proprietary Grasshopper plug-ins provide additional components which model a wide variety of phenomena, such as moving populations, energy usage, climate, fluid flows, or physical forces. These plugins can also integrate the model with other software.

One such type of proprietary Grasshopper plugins are called Smart Structural Interpreters (SSIs). The most popular of these is Geometry Gym, created and maintained by Australian engineer and programmer Jon Mirtschin. This component takes model geometry defined in Grasshopper, defines materials, sections, loads, and support conditions, and writes them to files that can be read by structural analysis programs, such as SAP2000. Geometry Gym can also retrieve the results from SAP2000 for further interpretation.

Additional Grasshopper plugins, such as Galapagos or Octopus, take these results and runs through a series of adjustments and alterations, in which SAP2000 automatically analyses and return results for with each iteration, to optimize the model to meet any desired fitness criteria.

The intended product of this research is to produce such a model especially tailored to CLT structures. At present the Geometry Gym interface has been prepared. Ongoing work includes writing custom CLT material components for Grasshopper using Python, and developing a series of form-finding/force-finding algorithms for curved or folded CLT shell structures.

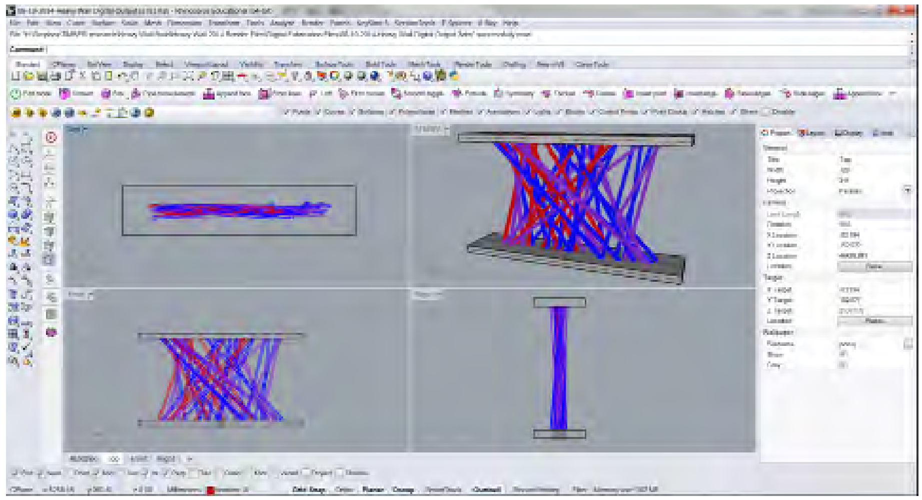


Figure 22. *Rhino 3D Interface*

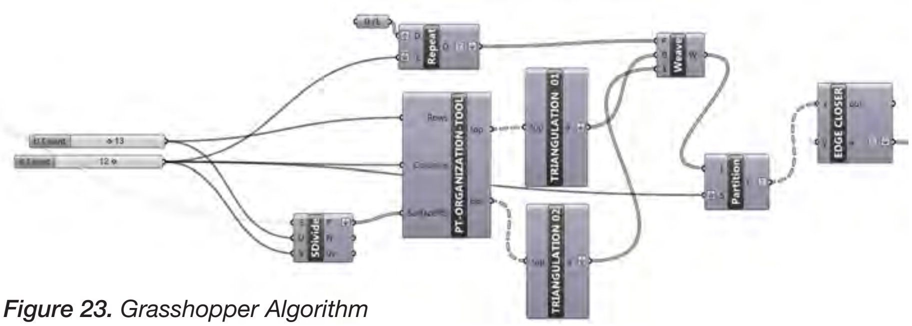


Figure 23. *Grasshopper Algorithm*

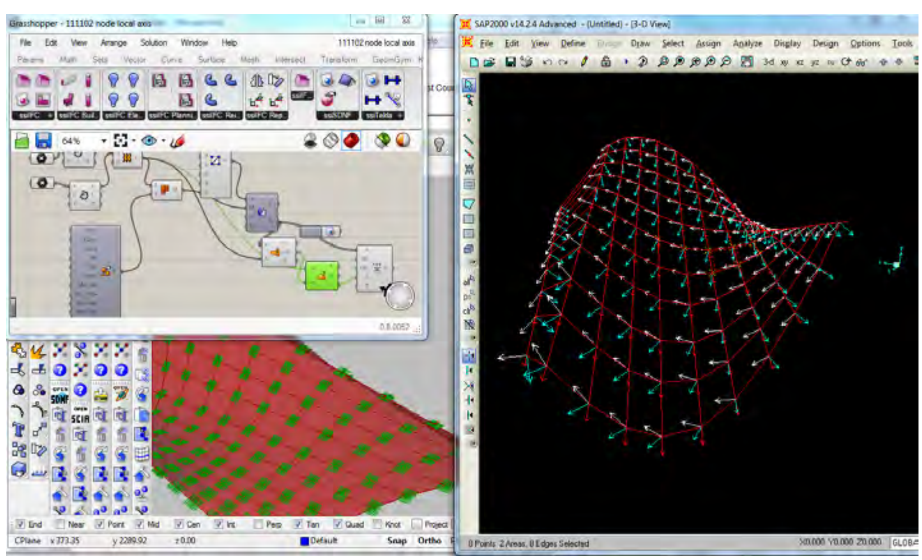


Figure 24. *Rhino 3D / Grasshopper / SAP2000 Connection*

IX. FABRICATION

xvii. INTRODUCTION

In order to create the dramatic forms of a doubly curved funicular structure in a seamless manner, we are currently devising a method of building doubly curved CLT panels. This method takes advantage of both the bending capabilities of dimensional lumber and the geometrical techniques utilized by traditional coopers (barrel makers). (Figure 26)

In the traditional wooden barrel making process planks of wood are slightly beveled to create staves. The staves are then placed within metal rings and bent to form a friction fit. In our process, dimensional timber is slightly bevelled using a CNC router to facilitate bending within two directions. The bevelled geometry allows the timber to form a curve in one direction while the stiffness of the wood along its grain allows us to bend in the second direction.

The timber layers are alternated in orientation to create the crossed laminations. The Rhino 3D based parametric generator that we developed to design the doubly curved panels adjusts the radius of each lamination to ensure a snug fit between all laminations. Furthermore, due to the symmetrical nature of the panels, each layer only requires two unique timber shapes - 1 middle piece which repeats the length of the panel, and 1 end piece which caps both ends of each lamination. (Figure 27)

At this time we are beginning to prototype these doubly curved CLT panels. At present we are experimenting with adhering the planks together with self tappign screws. Each layer is clamped into place and then screwed to the layer beneath. Future experiments will include adhering the planks with glue and nails. (Figure 28)

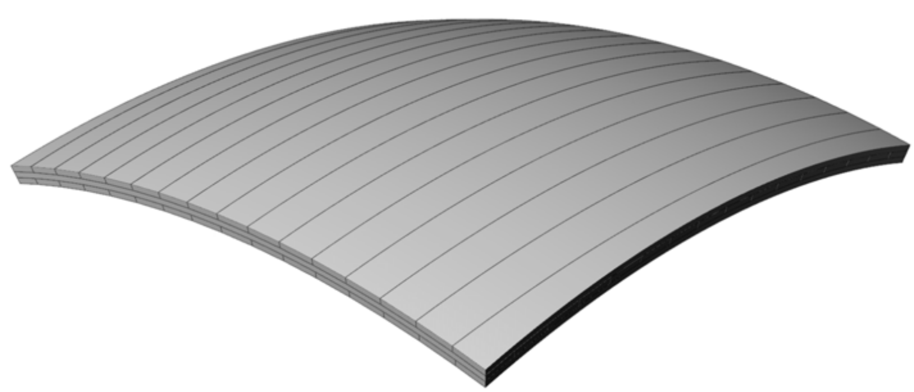


Figure 25. *Parametrically Generated Doubly Curved CLT Panel*

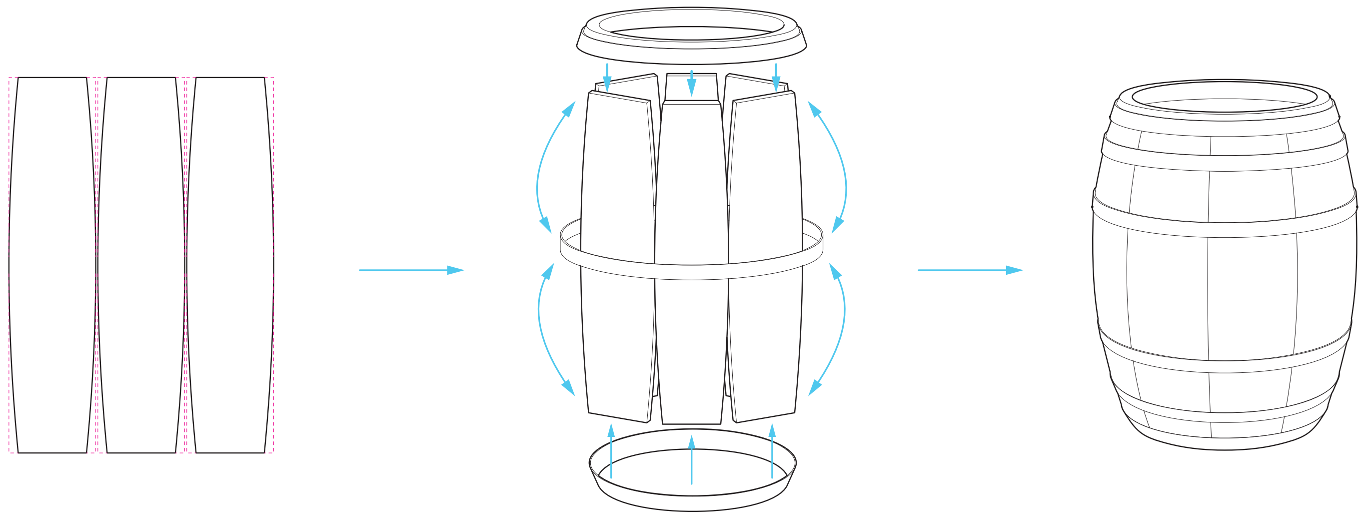


Figure 26. *Inspiration: The Barrel Making Process*

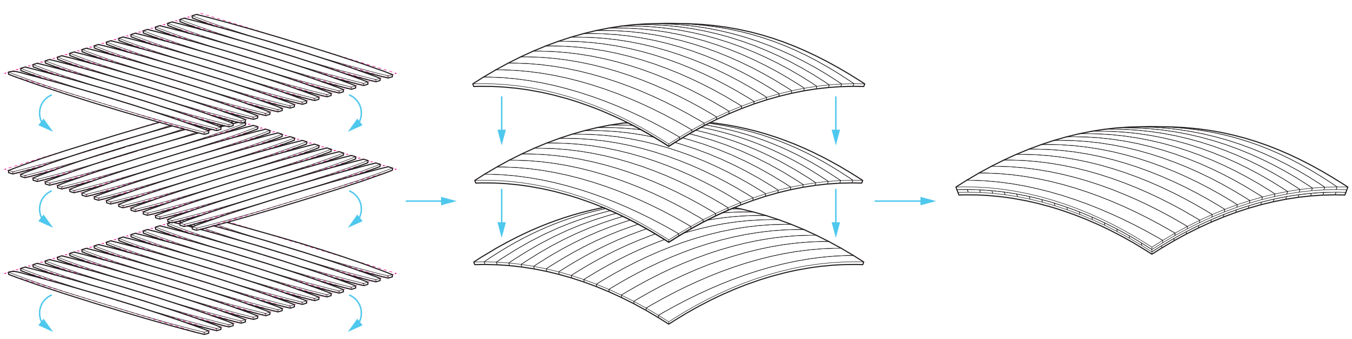


Figure 27. *Composition of a Three-Ply Doubly-Curved CLT Panel*

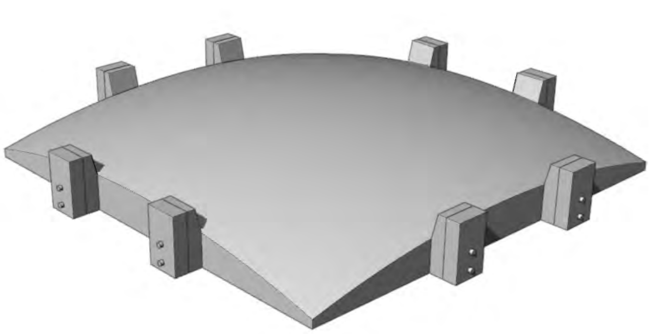


Figure 28. *Rendering of the final Positive Mold / Process Photo of the CNC'd Positive Mold*

xviii. DOUBLE CURVED CLT SCREW ONLY SINGLE CURVATURE - PROOF OF CONCEPT FOR GEOMETRY

The edge guides, to which the panel pieces will be screwed to, were firmly clamped to the mold [01] [02] [03].

Figure 29.

Figure 30.

Figure 31.

The dwg files sent by Thomas were used to define the cutting lines for each of the individual pieces of the double-curved cross laminated panel. The middle pieces are all identical in shape, while the two outmost pieces have different profiles.

In order to pursue the strategy of screwing each individual piece to place in the mold, Vincent added an additional lenght to both ends of all pieces (32), where the screws could be introduced and connected to the edge guides.

In a first inspection, the width of the middle pieces allowed them to sit adequately in the suction cups of the CNC machine (33). The outmost pieces, however, were too narrow for the suction cups. After trying to cut the middle pieces (presumably adequate in width), it was observed that the CNC's suction cups failed to hold these to place as well (34).

Figure 32.

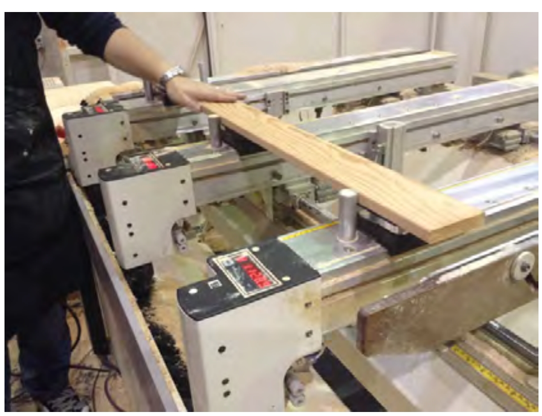


Figure 33.

Figure 34.

Therefore, the raw pieces of lumber started being screwed to a larger board [07] in order to secure firm grasp by the CNC's suction cups during cut (36).

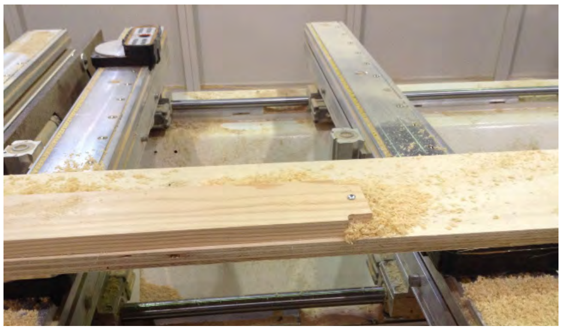


Figure 35.

Figure 36.

Figure 37.

The initial piece to be placed on the mold was first screwed to one of the edge guides (38)(39). After being screwed, the same end was clamped to the edge guide, in order to allow for safe bending of the piece (40) The bending was achieved using a second clamp in the opposite end of the lumber piece. With both ends of the piece securely clamped, the second end is screwed to the second edge guide (41).

Figure 38.

Figure 39.

Figure 40.

Figure 41.

In this first attempt, two problems were observed. First, a gap occurred between the lumber piece and the mold (42). Second, the lumber piece ruptured when the screw was introduced (43). The rupture problem was solved by employing a washer for distributing the load (44). The gap problem was not found to reoccur.

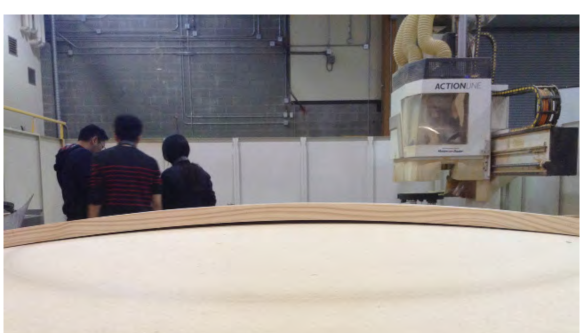


Figure 42.

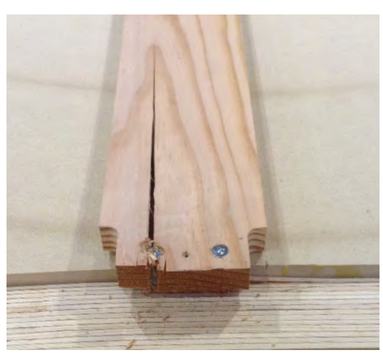


Figure 43.

Figure 44.

The second attemp to screw the middle piece to place was successful. [17] [18].

Figure 45.

Figure 46.

The subsequent pieces were added following the same procedure of the first (middle) piece. However, to avoid gap between the pieces, they were also clamped to each other before being screwed to the edge guides. Images (47) to (51) illustrate the fixation of the second piece.

Figure 47.

Figure 48.

Figure 49.

Figure 50.

Figure 51.

Images (52) to (57) illustrate the fixation of the 8th piece, following the same process as described for the 2nd piece.

In the next page, images (58) to (64) present the incremental process of fixing the 14 identical pieces of the panel's first layer.

Figure 52.

Figure 53.

Figure 54.

Figure 55.

Figure 56.

Figure 57.

Figure 58.

Figure 59.

Figure 60.

Figure 61.

Figure 62.

Figure 63.

Figure 64.

Finally, the outmost pieces were cut in the CNC machine (65). They were also fixed to the mold in the same process of the previous pieces (66).

The final assembly fit the mold perfectly in shape. The outmost pieces, however, were 1cm off the mold in both ends of the panel [40].

The first layer of the panel was successfully completed (69) (70).

Figure 65.

Figure 66.

Figure 67.

Figure 68.

Figure 69.

Figure 70.

xix. PANEL FABRICATION LAYER 2 - SCREW ASSEMBLY

All the pieces of the second layer were cut in the CNC machine in a similar fashion of those machined for the first layer. For the second layer, however, the CNC machine also marked the place of each screw (71). The number, positioning and angle of the screws were provided by Alex. The final file for cut was prepared by Vincent.

The students Evelyn and Vigoss worked on the assembly of the second layer.

In a first stage, all the timber pieces were drilled where the screws were to be introduced, in order to avoid the piece to split. The drilling, as well as the screwing, were executed in approximately 45 degrees (72), so that the screws could resist spring back force in tension. This angle was not accurate, since no tool was used for precise measurement.

Figure 71.

Figure 72.

After the screw holes in the pieces were drilled, the pieces were assembled one by one onto the panel's first layer, starting with the middle pieces.

First, the piece to be installed was secured to place. This was achieved by clamping both ends of the piece to the mold (73)(74). In order to prevent gaps between the individual pieces, a wooden mallet was used, forcing the piece together with the adjacent one previously installed (75).

After the piece was secured to place, the screws were introduced (76). Again, the process started from the center towards the extremities. The screws are not long enough to completely crosscut the first layer when inserted in a angle. Instead, they only attach the second layer to the first layer, leaving the mold intact.

Each individual piece in the second layer is attached with two screws to each individual piece of the first layer.

Figure 73.

Figure 74.

Figure 75.

Figure 76.

Figure 77.

Figure 78.

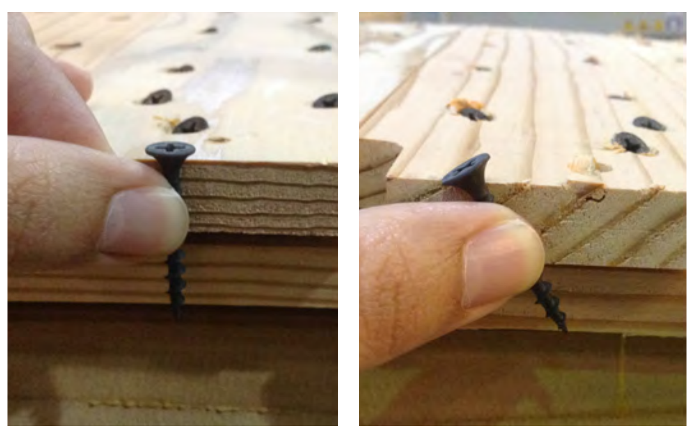


Figure 79.

All the pieces were installed following the same procedure (81-84).

The second layer of the panel was successfully completed, except for a few issues which will be discussed in the following pages.

Figure 80.

Figure 81.

Figure 82.

Figure 83.

A few issues were observed during the assembly of the panel’s second layer. One of the most relevant ones refer to the fact that the second layer has caused the deformation of the first layer, to which it was screwed. The force exerted by the timber pieces trying to spring back created a gap between the first layer and the mold (85).

It is also assumed that these same forces have created a gap bewteen the individual pieces of the first layer (86). These gaps were not preexistent.

Screwing has caused the edge pieces of the first layer to split partially (87).

The pieces in the second layer, similarly to the pieces in the first layer, were cut with an additional lenght. However this additional length in the second layer did not serve the same purpose as it did in the first layer. Although it assisted in attaching the pieces to a larger board that could be grasped by the CNC machine’s suction cups, it served no purpose during assembly. Furthermore, the overall length of the pieces were incorrect, not matching exactly with the length of the first layer (88).

Regarding fixation of the second layer onto the first one, the screws didn’t seem sufficient to secure a tight attachment in the extremities, leaving small gaps (89).

Finally, one of the edge pieces of the second layer could not be installed (89). The second later was not perfectly centered, leaving little space for the edge piece in one of the sides. Also, the screws securing the first layer to the side guides were salient, not allowing sequent pieces to overlay on them (90).

Figure 84.

Figure 85.

Figure 86.

Figure 87.

Figure 88.

Figure 89.

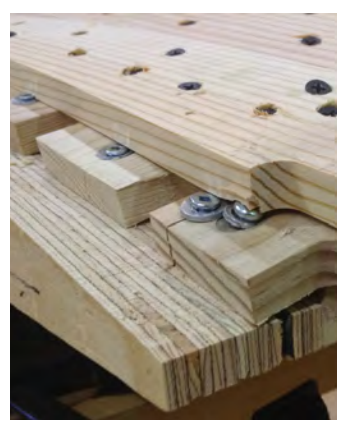


Figure 90.

DOUBLE CURVED CLT GLUE ONLY SINGLE RADIUS

Strategy: Glue only

Stage: Three layers out of three

Days: February 27, March 5 and 6

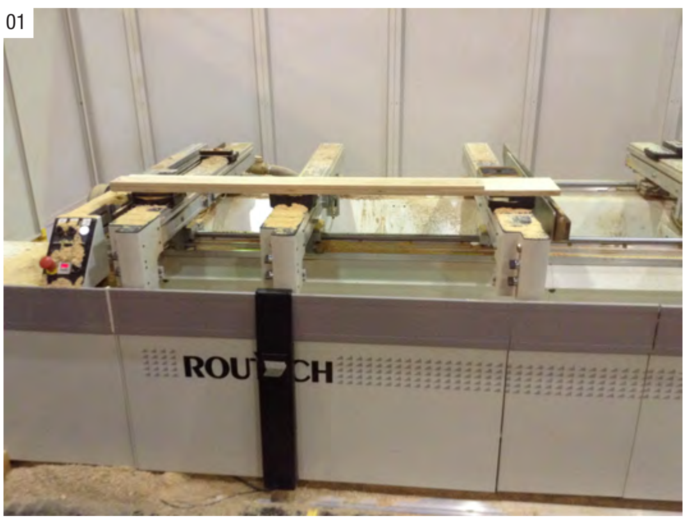
PROCESS

All the individual pieces of the doubly-curved cross laminated panel were cut in the CNC machine [01]. The pre-prepared planks were screwed to a larger board so that the CNC machine's suction cups had sufficient surface area to hold the pieces to place securely. The pieces were screwed to the board close to their extremities [02].

The pieces of the lower layer were cut with extra lengths to allow them to be screwed to side guides. For each layer, the middle pieces are identical in shape among themselves, while the two outmost pieces have different profiles. Image [03] shows all the pieces ready for assembly.

The MDF mold used to shape the CLT panel was the same mold already available from the previous doubly curved panel assembled using screws [04]. Because of this, the mold needed to be sanded to repair the damages caused by the screws[05].

01



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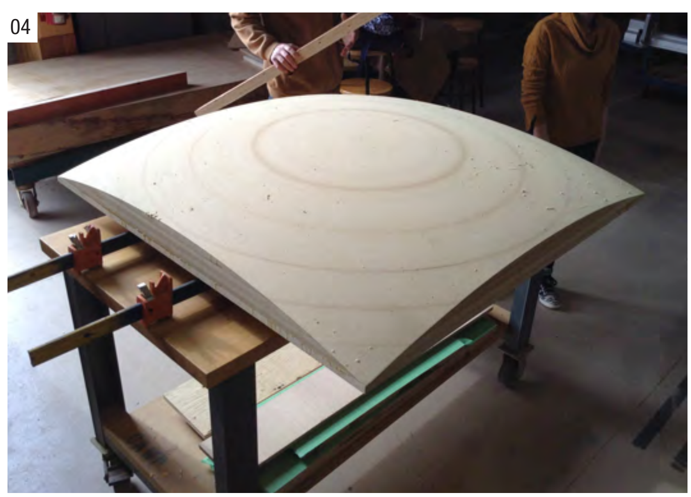

The side guides were marked according to the edge profile of the mold and cut accordingly [06].

In order to prevent the panel pieces from gluing to the mold, the mold was covered in plastic [07]. The plastic was stretched to present a plain surface and stapled to place on the sides of the MDF mold [08] [09].

Finally, the edge guides were attached to the sides of the mold using clamps [10].

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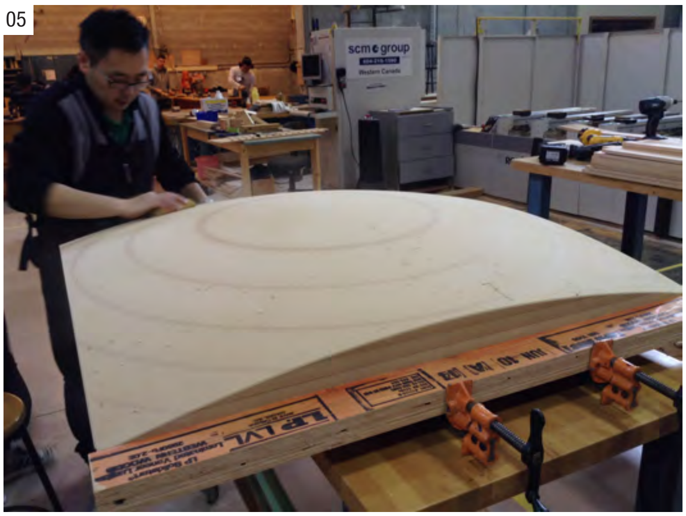

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For the installation of the first piece, the edge of the mold was measured and marked, indicating the exact location for this piece [11] [13].

The first piece was clamped in one of the extremities by the location marked [12] and then screwed to the edge guide [14]. The process was repeated on the other extremity of the piece [15] [16]


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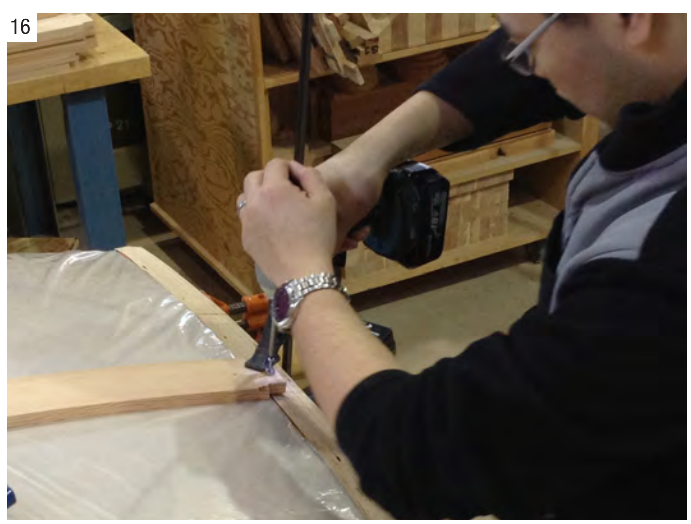
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All the other pieces were installed following the same procedure [17] [18] [19] [20] [21] [22] [27] [28].

After a few pieces had been installed, however, it was noticed that the edge guides were slightly slipping out of place. To fix this, a clamp was used to level the edge guides according to the edge of the MDF mold [23]. To prevent the edge guides from

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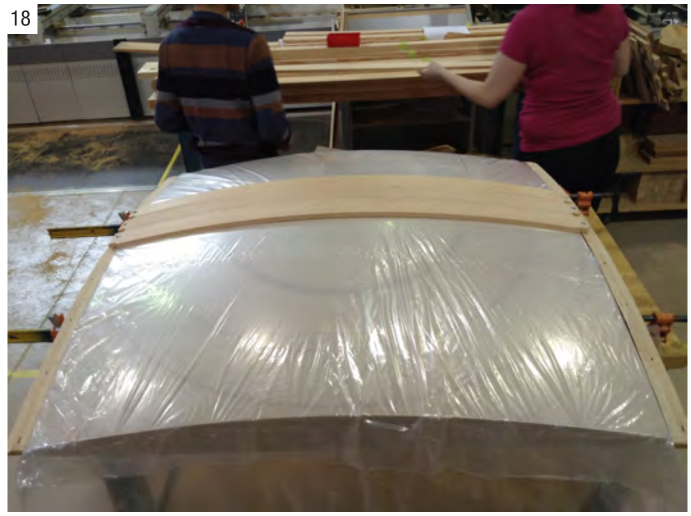

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moving again, they were screwed to the sides of the mold [24] [25] [26].

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After this problem was solved, the first layer of the panel was completed [27] [28], including the edge pieces [29] [30] [31].

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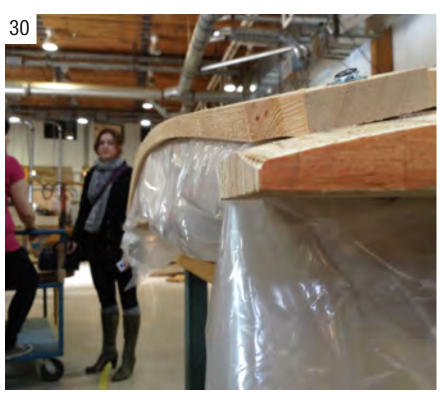

31


Right after the first layer was completed, the assembly of the second layer began. A central line was drawn indicating the location for the first piece of the second layer [32]. The first piece received glue on one of its sides [33] and was later clamped to the place [34]. All the other pieces followed the same procedure, however they had glue applied both to one side of the piece and to the place they'd sit on the first layer [35] [36].


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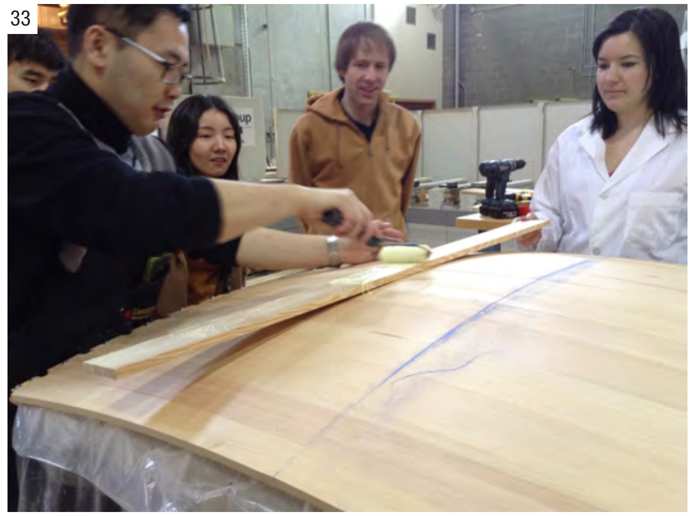
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Noteworthy, the pieces for the second layer were shorter than anticipated, given the final width of the first layer exceeded the size estimated. Thus each piece of the second layer was installed aligned to only one side of the first layer, alternating sides [37]. All the pieces of the second layer were successfully assembled following this same procedure already described [38] [39] [40] [41] [42] [43].

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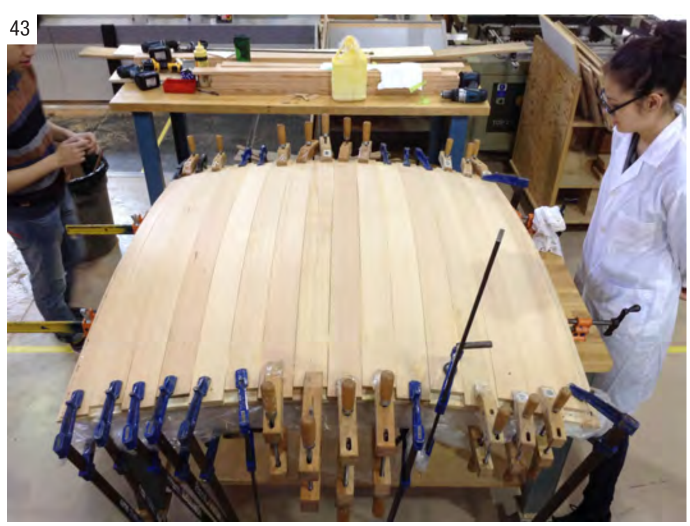

After the second layer was completed, the assembly was left to rest for at least 24 hours so that the clue could cure [44]. Given the fabrication team availability, the panel kept the clamps on for a total of approximately 144 hours (6 days).

In the first hours after the completion of the second layer, a few clamps fell out of place, releasing the pieces they were securing. It is likely that the clamps were slipping because of the plastic layer, which didn't provide good adherence surface for the clamps to grasp. The pieces that popped up due to the clamp issue had to be scraped and glued once again.

For the installation of the third layer, the same process that took place during the installation of the second layer was repeated. A central line was drawn indicating the location for the first piece of the third layer. All the pieces received glue on one of its sides and on the place they'd sit on the layer below, next being clamped to the assembly [45] [48] [49] [50] [51] [52] [53] [54] [55].

During the process, a mallet and an intermediate plank were often used to close gaps between a piece and another [46].

The clamps holding the second layer were kept in place until most pieces of the third layer were installed. These clamps were then removed successfully [47].

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After the third layer was completed, it was left to rest for 24 hours with all clamps on so the glue could cure [56].

The following day, all the clamps were removed successfully [57]. Next, the screws connecting the first layer to the side guides were removed. Some of the screws couldn't be immediately removed because the second and third layers were partially covering them [58]. Therefore these layers were carved to allow the screws to be removed [59] [60].

After all screws were removed, the panel still maintained most of its curved shape [61].

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THE FINAL PANEL

The doubly-curved panel was successfully completed on March 6, 2015 using glue only to connect the three layers [62] [63].

The assembly of this panel took approximately 5 hours and 50 minutes. These hours do not include the time spent in designing, preparing and CNC cutting the pieces.

In a preliminary test, the panel could support the weight of an adult person without visible deformation [64].

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COMPARISON WITH SCREWS-ONLY CURVED PANEL

While the panel using screws-only connections took approximately 14 hours to assemble, the same sized panel using glue-only connections took less than half that time (5:50). Despite the fact that a different number of people worked on each panel, not allowing for a rigorous comparison, the difference in speed was noticeable between the two processes.

Finally, the panel using glue-only connections maintained most of the mold's shape, unlike the panel using screws-only connections. The difference is visible by naked eye when comparing the two panels side by side [65] [66] [67].

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DOUBLE CURVED CLT GLUE ONLY TWO RADII

Strategy: Glue only

Stage: Three layers out of three

Days: March 16, 18, 20 and 23 of 2015

INITIAL PROCESS

The MDF mold used to shape the CLT panel was carved using a 3-axis CNC machine [01]. The mold surface was designed as a portion of a torus geometry, thus being doubly curved with a different radii for each of its two curved directions. Because of it's large size and the need for moving the mold to a different site [02], the mold was made in two different pieces which were later glued together

In order to prevent the panel pieces from gluing to the mold, the mold was covered in plastic. The plastic was stretched to present a plain surface and stapled to place on the sides of the MDF mold. Finally, two side guides were marked according to the edge profile of the mold and cut accordingly. The guides were attached to the sides of the mold using clamps [03] [04] [05].

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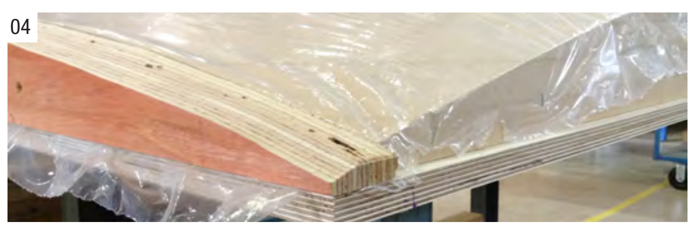

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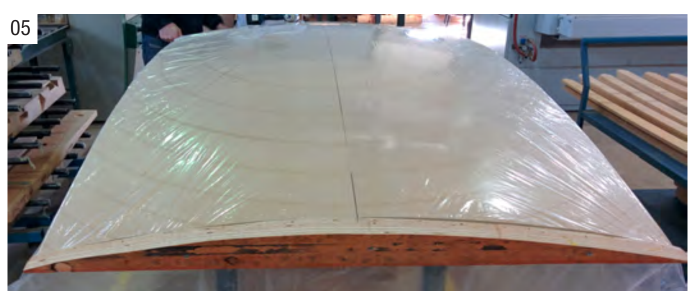

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All the individual pieces of the doubly-curved cross laminated panel were also cut in the CNC machine [06]. The pre-prepared planks were screwed to a larger board so that the CNC machine's suction cups had sufficient surface area to hold the pieces to place securely. The pieces were screwed to the board close to their extremities.

The pieces of the first layer were cut with extra lengths to allow them to be screwed to the side guides. The pieces of the first layer were designed and cut using an initial geometric logic which generated slightly curved pieces, each piece being unique [07].

The pieces of the second and third layer were only cut only after the assembly of the previous layer was complete.

ASSEMBLY OF THE FIRST LAYER

For the installation of the first piece, the middle one, the edge of the mold was measured and marked, indicating the exact location for this piece.

The piece was screwed to the edge guide in one of its extremities. Due to its length and radius of curvature, the piece could be bent easily without the assistance of clamps [08]. Thus, one person forced the piece to place on the mold, while another person screwed the piece to the guide in its second extremity [09].

The same process was used for all the following pieces of the first layer.

Importantly, however, because all the pieces are different, they had to be installed in the appropriate order and direction. To ensure this, the pieces had been numbered during preparation [10].

As more pieces were being installed, it became evident that a deformation problem was occurring. The pieces were not sitting properly on the mold, because their asymmetry was causing them to twist while being forced to place [11]. Applying weight on the pieces to force them to place did not solve the problem.

It was found, however, that turning the pieces in the opposite direction of the one intended during design allowed for a better accommodation of the pieces. Therefore, all pieces were removed, turned, and re-installed [12].

Initially, this strategy caused only the minor problem of small gaps [13]. As more pieces were being installed, it also revealed the problem of the edge pieces of the layer. The first layer ended up not having a rectangular footprint, but one a little curved in two of the edges [16].

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It was also noted that there was no sufficient room in these edges for the final pieces of the layer [17]. The team tried to install the two end pieces; however they were not properly supported [18] [19] [20]. Thus, the two end pieces of the layer were removed and disposed.

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Finally, in order to improve the fit of the pieces together onto the mold, a strap was used in the middle of the panel [21]. A mallot assisted in forcing some of the pieces to place [22].

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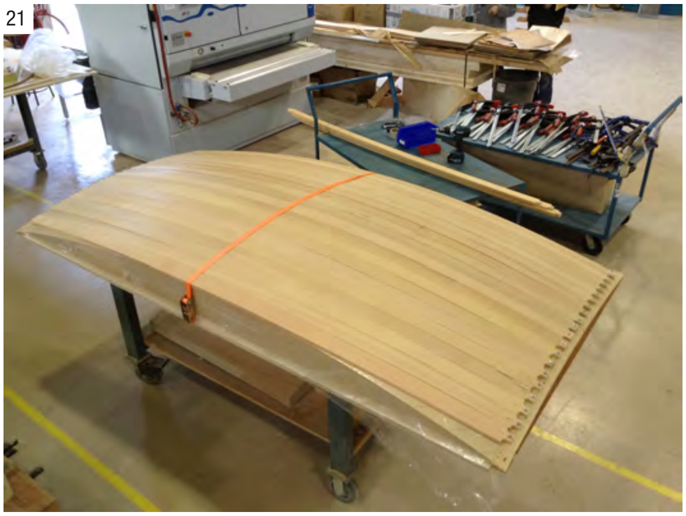

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ONE MORE TEST OF THE ORIGINAL GEOMETRIC LOGIC

Before advancing to the next layer, it was decided that the original geometric logic should be tested one more time, in order to confirm that the issues encountered during assembly were not a problem of installation.

All the pieces were unscrewed from the edge guides [23] [24] [25]. They were then carefully checked and placed according to the original plan [26].

Before reaching the final pieces, however, it was observed that it was not possible to continue. Each new piece added to place twisted more than the previous one. Once again, applying weight to the center of the pieces was not sufficient to force them to place [27] [28].

By removing one of the pieces, it became visible that the twisted pieces failed to touch the mold with most their lower surface [29].

After this new attempt to follow the original geometric logic for design and assembly of the first layer, the team considered the logic disproved.

Finally, all the pieces of the first layer were once again removed.

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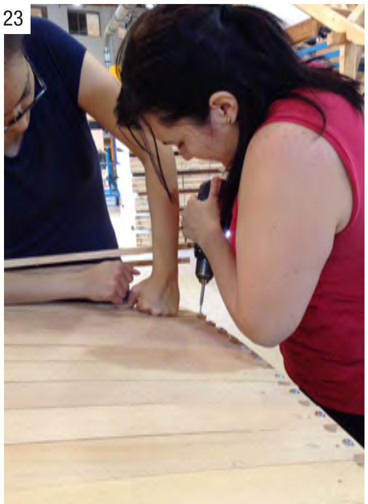
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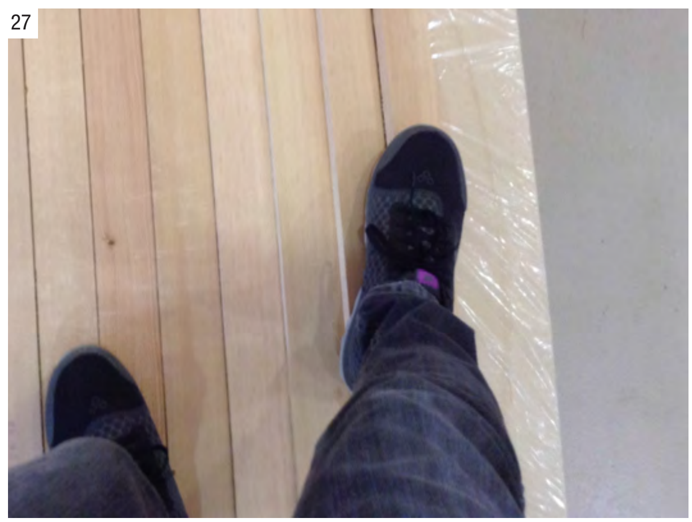
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REBUILDING THE FIRST LAYER

The first layer was reassembled in the same manner as it was completed the first time. A new set of pieces was not produced in order to save material, since the result of the first layer was considered acceptable, despite its issues. Image [30] shows the first layer after completion, prior to the installation of the second layer.

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ASSEMBLY OF THE SECOND LAYER

Because the initial geometric logic used to generate the pieces of the first layer presented difficulties, the pieces of the second and third layer were designed using the same geometric logic used to generate the previous doubly-curved panels (i.e. the barrel logic).

For both second and third layers, the middle pieces are identical in shape among themselves, while the two outmost pieces have different profiles. The middle pieces are also all symmetrical for all three orthogonal plans.

Concerning the second layer specifically, the middle pieces were not CNC machined. While prepping the files for the CNC, the team observed that the tapering of the center planks was so slight that it could be eliminated altogether. Thus, only the end pieces were machined on the CNC. The middle planks were cut to the calculated width. It was assumed that the resultant gaps were within tolerances of the panel.

All pieces were ready for assembly when the first layer was completed. Thus, right after the first layer was completed, the assembly of the second layer began. A central line was drawn indicating the location for the first piece of the second layer to be installed [31].

The first piece received glue on one of its sides. Glue was also applied to the surface of the first layer, where the piece was expected to sit [32]. The piece was then later clamped to the place one end at a time [33] [34]. All the other pieces followed the same procedure [35] [36] [37].

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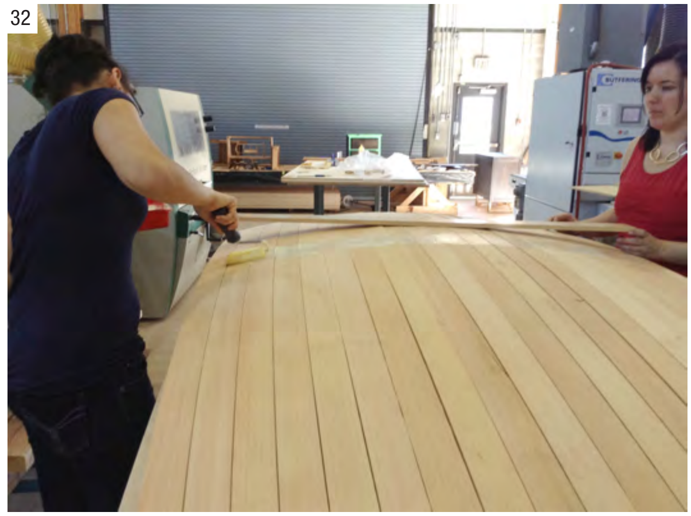

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In order to ensure that the gap between pieces was kept to a minimum, a mallot was used to force pieces closer together [38].

Noteworthy, the pieces for the second layer were shorter than anticipated. Thus, initially, each piece of the second layer was installed aligned to only one side of the first layer, alternating sides. Because of the issues in the design of the first layer, its footprint was not rectangular, but wider in the middle and narrower in the ends. Therefore, after the pieces of the second layer started becoming wider than the width of the first layer, the pieces started being aligned by the middle. To do that, all pieces were properly marked in the center [39] [40].

All the pieces of the second layer were successfully assembled following this same procedure already described [41] [42] [43] [44] [45] [46].

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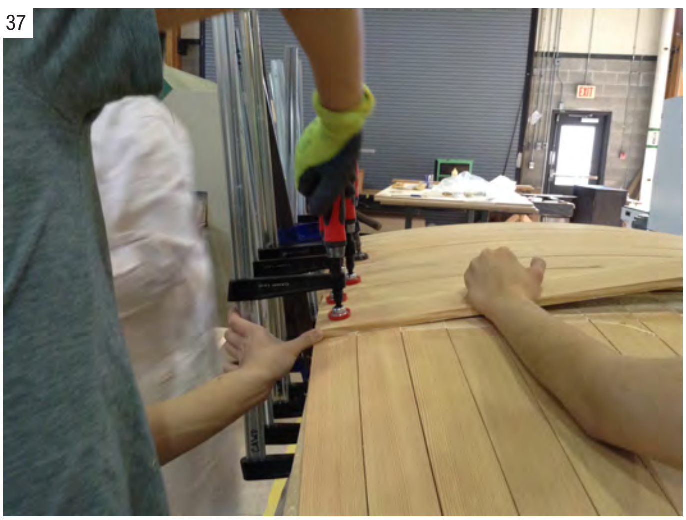

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Images [47] and [48] show that the pieces of the second layer perfectly fit on top of the first layer concerning length, with no adjustments required.

Because of the footprint issue, however, it could be observed that a significant gap was left under the second layer, in two of the edges [49].

After the second layer was completed, the assembly was left to rest for at least 24 hours so that the glue could cure [50].

A few gaps were observed between pieces after the completion of the second layer [51].


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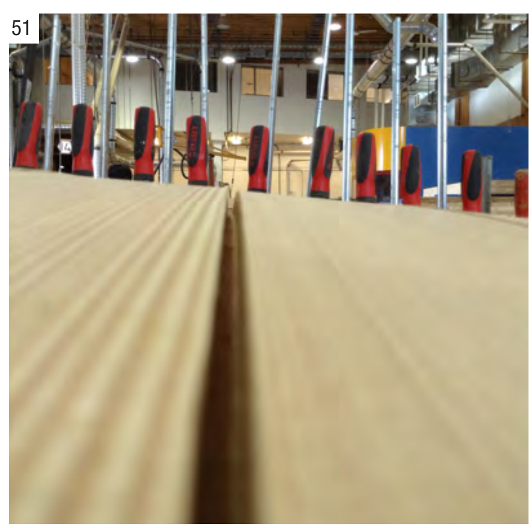
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THE THIRD LAYER

Prior to the installation of the third layer, all the clamps holding the second layer to place were removed [52]. The layer had been properly glued and maintained its shape after the removal of the clamps.

Without the clamps, the issues of alignment of the second layer's pieces in one of the dimensions became more visible [53].

To initiate assembly of the third layer, a central line was drawn indicating the location for the first piece of that layer [54] [55]. All the pieces received glue on one of its sides and on the place they'd sit on the layer below, next being clamped to the assembly [56] [57] [58] [59] [60] [61].

During the process, a mallet and an intermediate plank were often used to close gaps between a piece and another [59].


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This time, the layer composed a rectangular footprint. Despite the rough edges of the second layer, the end pieces of the third layer were accommodated satisfactorily. The pieces also fit perfectly regarding their narrower edge [62] [63] [64].

After all pieces were installed, additional pieces were added transversely [65]. These pieces were not glued to the panel. Their function was solely to assist in holding the assembly to shape.

The panel was left to rest for over 24 hours with all clamps on so the glue could cure.

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THE FINAL PANEL

When ready, all the clamps were removed successfully [66] [67]. Next, the screws connecting the first layer to the side guides were removed [68].

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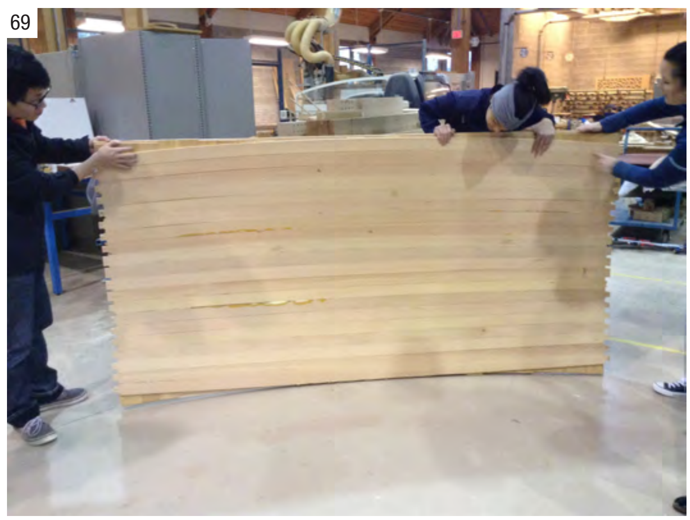

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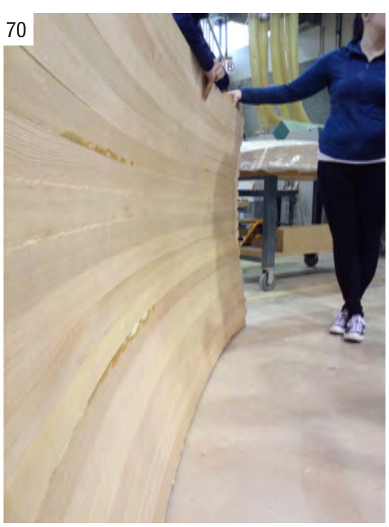

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After all screws were removed, the panel still maintained most of its curved shape. The doubly-curved panel was successfully completed on March 23, 2015 using glue only to connect the three layers [69] [70].

The assembly of this panel took approximately 7 hours and 50 minutes. These hours do not include the time spent in designing, preparing and CNC cutting the pieces. They do include the time disassembling and assembling the first layer twice.

In a preliminary test, the panel could support the weight of several adult persons without visible deformation [73] [74] [75].

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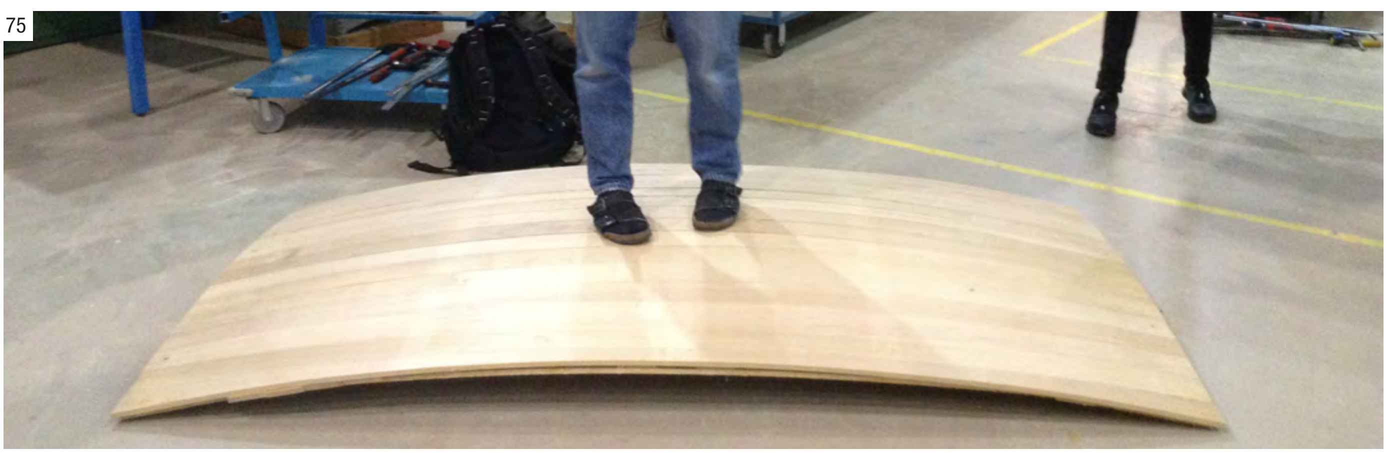

X. CONCLUSION

The research conducted has illustrated clearly the many avenues of research into new structural forms for wood. These forms would not be possible without the advanced design and analysis tools we have today, both in engineering and architecture. The research demonstrates that with these new tools, new forms can indeed be generated. The fabrication and engineering questions that they create indeed need much further research and we look forward to taking this research forward into a series of new research projects with the intention of building a wealth of knowledge for practitioners and fabricators to access.

FUTURE RESEARCH AREAS

In general all the structures types looked at need more research into the following:

envelopes - design and fabrication

connections - design and machining of detailed connections,

strength - quantifying the exact capacity of the structure, and

construction process - how to build efficiently.

DOUBLE CURVED STRUCTURES

The double curved CLT is a process of making the material itself whereas the other two types are using engineering wood products that are already available. As such, some additional particular research needs done on the double curved CLT.

Bounce Back

Fabrication prototypes indicated that the shells that are glued are much less likely to bounce back but there is still bounce back in the fabrication of the shells because we are bending laminations into place. It is unclear if thinner laminations and/or having an even number of laminations would cause this situation to be more predictable. The final prototypes and mold need scanned and the scans need compared in order to determine what the bounce back was and what the pattern of bounce back was and how it relates to the laminations.

Connection fabrication

These connections are very difficult due to the shell inaccuracy in the fabrication process as well as the inability of a typical 5 axis to cut the edges. Fabrication with an industrial robot may be the only way to do this and needs further research.

XII. BIBLIOGRAPHY

Bathon, L., et. al. (2009) *Holz-Stahl-Klebeverbindungen mit Flachkörpern – Etnwicklungen und Anwendungen*. Internationales Holzbau-Forum 09.

Canadian Construction Materials Centre. (2014). Evaluation Report CCMC 13677-R SWG ASSY VG Plus and SWG ASSY 3.0 Self-Tapping Wood Screws. National Research Councik of Canada.

Canadian Standards Association. (2010). CSA Standard, O86-10, Engineering Design in Wood, ON, Canada, 2010.

Canadian Wood Design Council, (2010). Wood Design Manual 2010: A complete reference for wood design in Canada.

Chans, D.O., Cimadevila, J.E., & Gutierrez, E. M. (2008). "Glued Joints in Hardwood Timber: International Journal of Adhesion and Adhesives 28 (2008) 457-463

Closen, M. (2013) "Tech Talk—CLT Sandwhich Connections". My-Ti-Con Timber Connectors Inc., Surrey, BC.

Custodio, J., Broughton, J. & Cruz, H. (2009) "A Review of Factors Influencing the Durability of Structural Bonded Timber Joints" International Journal of Adhesion and Adhesives 29 (2009) 173-185.

D'Amico, B., et. al. (2013) "Timber Post-formed Gridshell: Digital Form-finding / drawing and building tool". Proceedings of the International Associaton for Shell and Spatial Structures (IASS) Symposium 2013, Wroclaw University of Technology, Poland.

ETA – Denmark (2010). "European Technical Approval ETA-10/0189: Knapp Clip Connectors". 118.

-- (2013). "European Technical Approval ETA-11/0190: Wurth self-tapping screws". 99.

Fischer, T. et.al. (2012). "Sewing Timber Panels : An innovative digitally supported joint system for self-supported timber plate structures". Beyond Codes and Pixels: Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia, 213-222. Association for Computer-Aided Architectural Design Research in Asia, Hong Kong.

food4rhino.com

Gagnon, S. & Popovski, M. (2011). “Chapter 3: Structural Design of Cross-Laminated Timber Elements”. CLT Handbook. FPInnovations.

Gagnon, S. & Pirvu, C. (2011) *CLT Handbook: Cross-Laminated Timber.* FPInnovations.

geometrygym.blogspot.ca

grasshopper3d.com/group/geometrygym

Hassis, M. & Weinand, Y. (2008). “Origami – Folded Structures, Engineering”. Laboratory for Timber Constructions, Ecole Polytechnique Federale Lausanne. 1-7.

Jaksch, S., Fadai, A., & Winter, W. (2012). “Folded CLT Structures – Development in Design and Assembly Strategies”. Proceedings for the World Conference on Timber Engineering, Auckland 2012.

Jokerst, R.W. (1981) “Finger-Jointed Wood Products”. United States Department of Agriculture, Forest Service, Forest Products Laboratory. Research Paer FPL 382.

--(1982). “The Effect of Geometry on the Performance of Structural Finger-Joints”. Forest Products Laboratory, University of Wisconsin, Madison. 169-180.

KNAPP Connectors. (2014). “Connection systems for smart structural engineering: Design Guide”. 1-24.

LaMagna, R., Waimer, F., & Knippers, J. (2012). “Nature-inspired generation scheme for shell structures” Institute of Building Structures and Structural Design, University of Stuttgart. 1-7.

Lehmann, M., et. al. (2013). “Adhesively Bonded Joints Composed of Wooden Load-Bearing Elements” Bern University of Applied Sciences, Biel. 1-9.

Mirtcshin, J. (2011) “Engaging Generatimve BIM Workflows”. www.rhino4you.com

Mohammad, M. (2010) “Connections in CLT Assemblies”. Seminar on CLT Construction, Quebec City, QC 2010. FPInnovations.

Mundell, N. (2013) “We <3 the Geometry Gym Plugins for Grasshopper”

Robeller, C., et.al. (2014). “Design and Fabrication of Robot-Manufactured Joints for a Curved-Folded Think-Shell Structure Made from CLT”. Robotic Fabrication in Architecture, Art, and Design 2014. Springer, 67-81.

Schimek, H., Meisel, A., & Bogenperger, T. (2014). "On Connecting Panels of Freeform Building Envelopes". Graz University of Technology. 1-8.

Structurlam. (2013) "Cross Laminated Timber Design Guide". Pentiction, BC.

Tas, L.M. (2013). "Curved Folded Timber Plate Structures: Numerical and Geometrical Research into the Structural Behavior of Curved Folded Systems". Masters Thesis, Eindhoven University of Technology. 1-140.

Thornton Tomasetti. (2014) CORE Studio Brochure. core.thorntontomasetti.com

TiComTec GmbH. (2010) *Eingeklebte Stahlstäbe – Gewindestabe – Betonstähle.* Technisches Dossier Stahlstäbe-2010-08.

Vrazel, M. & Seller, T. (2004). "The Effect of Species, Adhesive Type, and Cure Temperature on the Strength and Durability of Structural Finger-Joints." Forest Products Journal 54 (3) 66-75.

Weinand, Y. (2009). "A New Generation of Structures". Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia. 1-8.

Wurth, A. (2013) *European Technical Approval ETA-11/0190*. English translation provided by Deutsches Institut für Bautechnik.