Large Scale Wood Surface Structures

Alex Cheng, Oliver Neumann, Annalisa Meyboom, Thomas Tannert

***Abstract*—Advanced digital fabrication processes afford architects the opportunity to realize parametrically designed surface structures. Wood is a well-suited material for these types of structures since it can be machined easily. More research, however, is required to demonstrate the feasibility of engineering and fabricating of these designs. This paper describes the approach and structural criteria required for investigating the feasibility of designing large-scale surface structures in wood using the latest parametric design processes and digital fabrication technologies. Engineered laminated panels such as cross-laminated timber or variations of such products including double curved structures are investigated as part of the described study.**

Keywords- ***parametric design, digital fabrication, surface structures, folded plates, shell structures, wood design***

I. Introduction

Shell and folded plate structures show potential for spanning larger interior spaces such as gymnasiums, community centres, schools, churches, general large entry spaces, and circulation areas. They provide large column free spans, and are highly structurally efficient [1]. The larger intention of this research and a future research trajectory is to expand the idea of wood as a malleable and curved structural material to make it the material of choice when architects and engineers desire a curved surface.

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 difficulty manifesting these designs. With current digital fabrication tools, wood has the potential to be the material that allows to easily and inexpensively produce curved forms [2]. Research needs to be done in order to demonstrate the feasibility of engineering and fabricating of designs.

The potentials of digital modeling, simulation and fabrication provide an increased ability to design curved and complex structures. Wood has the potential to respond well and facilitate designs but this has not yet been fully explored due to the newness of the fabrication technologies and the engineering uncertainties that come with engineering and fabricating such a structure. This research looks at what the systems might be what the potentials of the systems are and defines what aspects of structures need further engineering knowledge or can benefit from the integration of disciplines.

II. Membrane Structures in Wood

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 seems to defy gravity.

When we consider surface structures in architecture, wood has traditionally not played a large role. However, current digital manufacturing techniques and highly advanced analysis capabilities are able to change this limitation [3]. Wood is easy to machine and can be additive or subtractive in its manufacturing and construction processes. Wood is valued in architecture for its colour, texture, smell, tactile and light reflecting properties. It is also highly sustainable and can function as structure, ornament, finish or enclosure. Surface structures take advantage of all of these properties in wood.

Although seeming to deny gravity, surface structures are derived from gravity itself. Gaudi, Frei Otto and Heinz Isler and more recently Toyo Ito's Funeral Hall in Kakamigahara provide us compelling examples of form finding and the funicular forms. Surface structures are to date mainly completed in concrete due to its malleability. But with new digital fabrication equipment, wood could be the material of choice for these structures. Wood shell and folded plate structures are approximated to be the same thickness as their counterparts in concrete and are more efficient in that they are lighter and do not require the sacrificial formwork to build them. In addition they store carbon rather than consume it, making them much more desirable from a sustainability perspective.

Other approaches to surface structures can also be demonstrated by a folded plate or rippled structure, whose fold depth provide its bending resistance. These surface structures use their global geometry to give strength, maintaining lightness while their depth provides structural stability.

III. Background on State of the Art Engineering and Fabrication for Timber Shell Structures

Shell structures in wood are rare as they are complex; they lack specific design guidelines or tools. Three past precedents of timber shell structures are briefly outlined here. They provide examples of current state-of-the-art engineering, fabrication, and design methodologies. These references have been used as guidelines in our project.

The Nine Bridges Country Golf Club in Korea (2008) is a long span timber grid-shell which seems to pour over a hilly topography. It consists of curved glulams that form a hexagonal network. This network is divided into sections for prefabrication that were then erected and secured on site with steel plates and braces [4].

The Landesgartenschau Exhibition Hall and the 2011 Research Pavillion by the ICD at University of Stuttgart (ICD, ITKE) are short span shell structures; they are comprised of finger-jointed panel assemblies. In the case of the 2011 Research pavilion these panels form cellular units. As the finger joints could transfer no moment and relied on in-plane shear forces for stability, the precision of the finger joint was critical and required a 5-axis robot for their fabrication. STS are used for moment transfer; they are also used to join individual panels of the Landsgartenschau Exhibition Hall and the cell units of the 2011 Research Pavilion[5].

Most recently, the roof of the Elefantenhaus at the Zurich Zoo (Markus Schietsch Architekten, 2014) consists of triple, alternating layers of Cross-Laminated-Timber (CLT) panels. Each panel was assembled over singly-curved formwork and then pre-cut according to the pattern of apertures.. Three layers of curved panel pieces were built-up over scaffolding during construction and secured with long STS; later, chainsaws were used to cut out finesse the apertures, leaving behind a varied network of solid timber secured by a reinforced concrete tension ring at the roof edge [6,7].

While these celebrated timber structures vary in form, concept, and execution, all were executed at the design stage using parametric models, owing to their complex geometries. It is therefore the methodology of their design, not just the structural concepts, which is critical to the implementation of these structures.

This research seeks to combine the long spans provided by glulam grid shells with the solid panel aesthetic demonstrated by the works from ICD and Markus Schietsch Architekten, all while using structural CLT panels fabricated with curves or assembled into folds to achieve a greater degree of geometric variation, severity, and material efficiency than could be achieved in the Elefantenhaus.

IV. STRUCTURE TYPES

The structure types considered in the study all involve CLT panels explored in different formal typologies. The reason for the interest in CLT panels is that they afford structural capacity in both in-plane directions. Engineered wood products are opening up new avenues for architects to investigate. When there is material innovation, there can be architectural innovation; engineered wood affords the prospect of new architectural forms. The potential for these panels has been broken down into three main structure types: the first is a folded plate structure (Figure 1), the next variation is a lapped panel (Figure 2); and most complex, a double curved CLT structure (Figure 3).

V. PARAMETRIC AFFORDANCES

The investigated forms would not be possible without the ability of architects to design with parametrics. The structures require digital computing to manifest them. Realization of these designs requires an ability to model them, both in architectural as well as engineering software, as well as the ability to fabricate them. Each of these steps requires advanced tools in each of the three areas: architectural design, engineering design and digital fabrication.

One of the advantages parametrics affords architecture is 'cheap variation.' By this we refer to the ability to accomplish variation with minimal investment in time or effort by the designer. This can be thought of in two ways: first is the variation in design options while designing, for example by changing the lengths or widths of elements and by examining the effect of this change in order to choose an option. Second and more relevant is the ability to vary elements within the design itself with little effort. One concern issue with this second version is that it may be relatively easy to design but that it may not be easy to build a variation.

If the architect understands the material and fabrication processes, however, knowledge about the material and the fabrication process can be incorporated into the parametric model and the resulting design can reflect such design input. In this research, we have attempted to quantify panel limits and joint conditions to understand what parameters we need to design within.

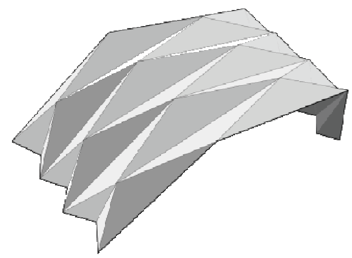

Figure 1. Folded Plate Structure

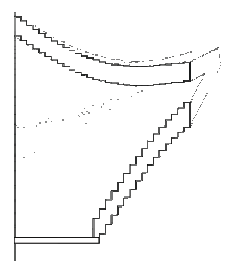

Figure 2. Lapped Panel Structure

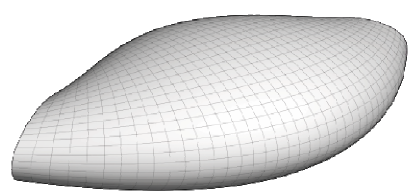

Figure 3. Doubly Curved Shell Structure

A. *Integration of Architectural and Engineering Models*

Rhinoceros [8 is a 3D NURBS Modelling software. Lines and surfaces are based on numerical algorithms. The Rhinoceros plug-in Grasshopper provides a visual programming language, bypassing the drafting user interface [9]. Algorithms and parameters are manipulated directly by connecting 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 a model with other software.

One such type of proprietary Grasshopper plug-ins are called Smart Structural Interpreters (SSIs). Geometry Gym is one of the more popular SSI[10], which takes model geometry generated and parameterized in Grasshopper, defines and assigns materials, sections, loads, and support conditions to the model, and writes them to files that can be read by structural analysis programs, such as Autodesk Robot[11]. Geometry Gym can also retrieve the results from these programs for further interpretation. Additional Grasshopper plugins, such as Galapagos or Octopus, iteratively adjust the model parameters based on results provided by the structural analysis program, in order to optimize the model to meet any desired criteria.

The intended product of this research is to produce such integrated models especially tailored to CLT structures. At present, the Geometry Gym interface has been prepared. Ongoing work includes the writing of custom CLT material components for Grasshopper using Python [12], as structural analysis programs contain no built-in values which properly describe the material behavior of CLT, and the development of a series of form-finding and force-finding algorithms for curved or folded CLT shell structures.

VI. STRUCTURAL LIMITS AND PARAMETERS

A. *Initial Assumptions and Considerations*

Geometric morphologies and mutations require cutting standard CLT panels into smaller angled shapes and sections. Usual design protocols assume sizes of CLT panels based upon 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: spacing requirements for proposed connections, curvature limitations, simple span deflection estimates, and fabrication constraints.

However, it is worth considering that connection costs could be significantly higher when the panels are smaller since an assembly consisting of many small panels will require more connections than a few large panels covering the same span. The cost of connections could become significantly more than the cost of the panel itself; this fact this may be a limiting condition in a design [13]. Also worth considering is that thinner panels will lead to thinner structures and therefore shorter spans. When significant spans are required panel sizes will be larger by necessity.

B. *Material behaviour*

CLT panels are characterized by alternating laminations of wood that provide high bi-axial in-plane strength and shear resistance [14]. As such, a CLT panel is somewhat 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 Stiffness $(GA)_{eff}$ of each panel type were calculated based upon Shear Analogy provided in the CLT Handbook [15].

ii) Laminae consist of Douglas-Fir-Larch timber, grade No. 2 or better: material properties are taken from CSA-O86 2010 [16].

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 research conducted at the University of Bath[17].

C. *Initial Assumptions*

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 [15]. Additionally, individual panels have been simplified as simply-supported one-way beams. Doing so allows Kreutzinger's Shear Analogy Method, considered the most precise [14], to be used to determine effective bending stiffness and shear moduli, which are necessary to determine panel capacity and deflection. Therefore, curved or folded CLT plate structures can be modeled conservatively as gridshell or complex truss assemblies [16]: this greatly simplifies digital form-finding and finite element analysis iterations. Table I lists recommended panel size limits.

VII. VII. PROPOSED CONNECTIONS

Connections are another critical consideration when designing wood structures. Those connection systems that best utilize the strength of CLT panels have, like CLT panels themselves, no design guidelines in CSA-O86 2009 [17]; the designer must refer to European proprietary systems. While Eurocode 5 [19] provides equations for some systems, more detailed design guidance for each system type is provided by individual manufacturers in the form of European Technical Approvals (ETAs).

TABLE I. RECOMMENDED PANEL SIZE LIMITS

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”

A. *Self Tapping Screws*

STS are the industry standard connection system in Europe for CLT panel assemblies [20]. These screws are made from high capacity steel, need no pre-drilling, and are easy to install. Properly designed STS connections are highly efficient, practical, and easy to hide by countersinking their heads into the panels and filling the holes with wooden inserts.

These connections function by forcing the screws into tension and the wood into compression. They perform best when screws are inserted at an acute angle to the grain direction of the outer layer. Only the threaded section embedded in the main member, which is the CLT panel containing the tip of the STS, provides resistance [21], and is termed the effective length (l_{eff}). The insertion angle may therefore be adjusted to maximize l_{eff}. End-grain installations should be avoided: screws installed in the narrow edge of a CLT panel therefore need precise installation to evade this condition or need to be avoided altogether [21].

The Canadian and European product approvals for SWG STS provides detailed design guidance and spacing requirements, summarized here according to their controlling design parameters:

(a) screw diameter *d* is at most one-tenth of an individual panel thickness. The total length of the screws must not allow it to protrude from the panel assembly.

(b) the CLT panel face in which the screw is inserted: the assemblies under investigation consist only of screws inserted into the wide face of a CLT panel, either perpendicular or at an acute angle to the grain direction of the outer layer.

(c) screw configurations: connections often consist of pairs of crossed screws: provide a 2*d* distance between the shafts of crossing screws; separate arrays of individual screws, either perpendicular or angled, or pairs of crossed screws by 4*d*. Providing a minimum 6*d* edge distance "margin" at the perimeter of all STS connections should accommodate any of the proposed the connection configurations.

All plate configurations under consideration in this investigation are well-suited for STS connections.

B. *Glued-In Rods*

For glued-in rod connections holes are drilled into the wood, filled with adhesive, and then set with rods. These connections provide high strength, invisible moment connections. For a ductile connection rods may either be carbon fibre, glass fibre, or steel. An ideal connection would achieve a smooth force transfer between multiple small rods, thus minimizing stress concentrations in the connection. Unfortunately, no consensus exists on their design and research into optimum rod diameter, spacing, and embedment length into the panel is ongoing[22]. Multiple rods require more holes and panel preparation, which increases costs. Additionally, proper assembly of these joints is not only difficult to achieve on-site but, owing to their embedded nature, also difficult to inspect and confirm, and this must be taken into consideration when choosing a connection type. For the structure types under consideration in this investigation, glued-in rods may be applied to the valleys and apexes of folded assemblies and butted panel connections where aesthetics absolutely demand exposed panel surfaces and invisible connections.

C. *HSK Plates: Adhesively Bonded Perforated Steel Plates*

HSK plates, short for *Holz-Stahl-Klebeverbindungen* ("wood-steel-glue connections"), is a strong yet ductile connection system with excellent shear and moment resistance [23]. A matrix of small holes is cut out of thin steel plates. The installation of these plates is straightforward and similar to glued-in rod connections: narrow slots are cut into the wood off-site. Spacing of slots vary based on loading condition, but do not govern panel size recommendations for this investigation. On-site, the slots are filled with adhesive and then the plates are set into the slots; prepared wood panels are slid over the protruding plate ends.

Though straightforward, the combination of pre-fabricated CNC machined CLT panels and adhesives makes this an expensive option. Like glued-in rod connections, HSK plate connections are best-suited for structures with considerable loading demands and aesthetics which require exposed CLT panels with nearly-invisible connections: i.e., the angled seams between "folded" CLT plates.

D. *Finger Joints*

Finger joints have been identified as a key way of passing in-plane shear loads between panels in experimental timber pavilions [24], as illustrated by Achim Menges' work with the Institute for Computational Design. Several of their Research Pavilions exhibit successful larger-scale joints for jointing plywood panels. This implies that such joints are potentially possible with CLT panels, though none have yet been attempted. In this vein, finger jointing may therefore also play a role in augmenting the other connection types above.

E. *Conclusion*

With these material and connection considerations in mind Table I lists panel sizes related to the deflection limits of simply supported CLT panels, which give baseline guidance to the maximum panel sizes for a structure, and the minimum panel length and breadth dimensions based upon the connection requirements for STS.

VIII. Curvature Limitations

Glued-laminated timber beams have long been manufactured with a small amount of curvature to mitigate deflections [25]. 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. Although not common, single curvature CLT panels are manufactured in Europe by building-up and curing the laminations over formwork, much like the manufacture of curved Glulams. Table II and Figures 5 and 6 illustrate the relationship between lamina thickness and the smallest allowable radius of curvature (Rc) according to CSA-O86 2010 [14].

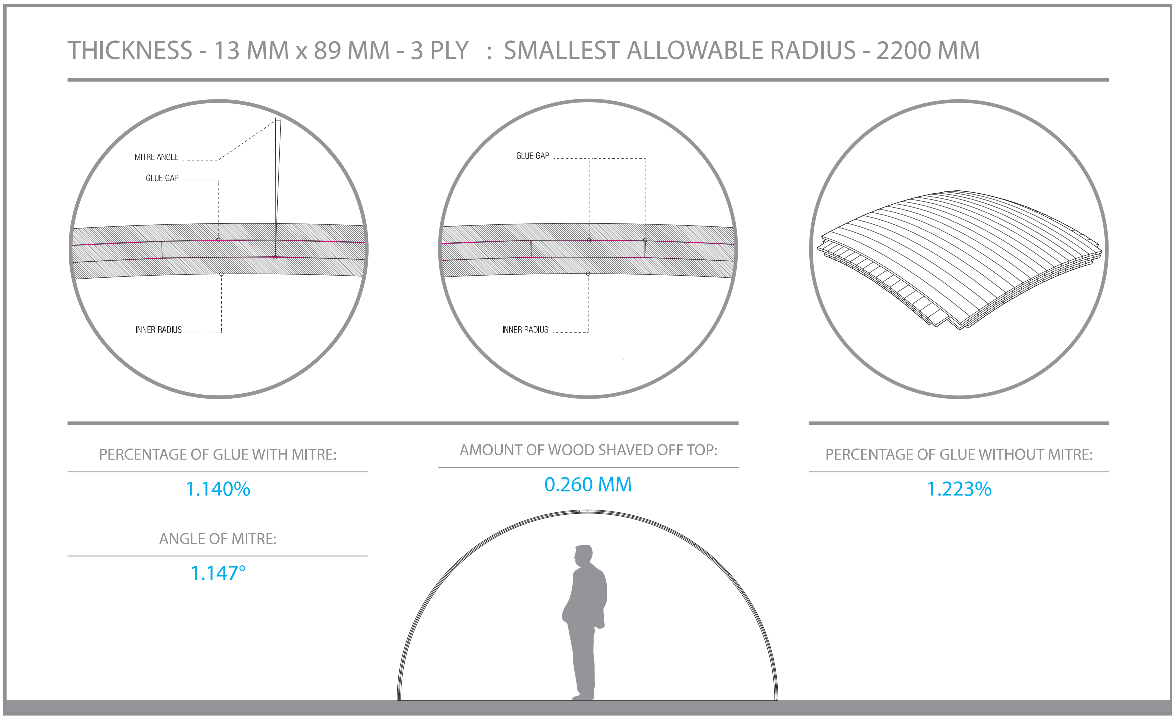

Figure 5. *Curvature Illustration - 13 mm x 89 mm*

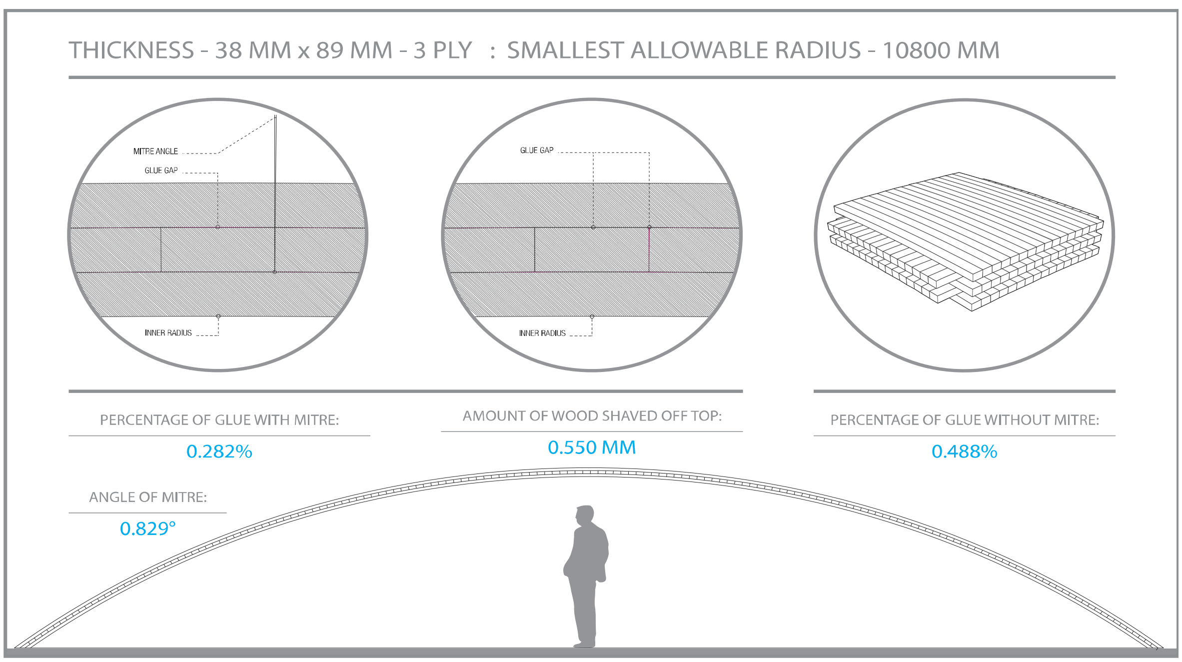

Figure 6. *Curvature Illustration - 38 mm x 89 mm*

IX. MANUFACTURING CONSTRAINTS

Equally important to structural requirements when considering hi-tech timber systems, are manufacturing constraints. In order for a product to be adopted by the industry, it‘s production must be feasible using 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. Our accessibility to these machines and the fairly ubiquitous nature of such technologies such as a CNC machine assure that not only will prototyping at the research phase be streamlined, but also that industry could adopt the outcomes of this research quickly. Table III shows the limitations of different machines that have informed our research.

X. FURTHER RESEARCH

This research is part of an ongoing project to investigate the potential of large scale curved and folded CLT systems. Future research will explore the limits of the systems architecturally, demonstrating the potential of the systems and further refine and define jointing possibilities. Further development of the architectural integration with FEM modeling and full scale prototypes of the wall systems will be built.

TABLE II. CURVATURE LIMITS RELATIVE TO INDIVIDUAL LAMINATION THICKNESSES (TAKEN FROM CSA-O86 2010) [24]

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 III. MACHINE SPACE OF VARIOUS ADVANCED DIGITAL CUTTING MACHINES

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

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