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Timber Shell: Wood in Building

Oliver Neumann[1], Jessica Hunter[2], AnnaLisa Meyboom[3], Alex Cheng[4], Thomas Tannert[5]

Abstract

Contemporary design technology has given architects the ability to imagine and visualize complex structures to an extent that is currently beyond our ability to effectively fabricate and build. The described research is intended to mediate between the imagination of the designer and the current modes of construction; this project is part of a larger proposition to use wood as a sustainably sourced material that can be formed, curved and machined to create new digitally produced and tested formations. TimberShell creates prototypes for full-scale timber monocoque structures. Material computation affords us the ability to use the natural bending properties of wood to both bend components into shape and to create a robust load carrying structure once individual wood components are locked in by lamination. The geometry of the shell panel eliminates twisting. The research shows how doubly-curved timber shells that can be applied in either tension or compression. The panels can be used to create and cover spanning structures such as pools, gyms and auditoriums.

Keywords: Shell structure research, spatial applications

1. Introduction

Contemporary designers have unparalleled agency. New technologies have provided novel facility for performance evaluation, form generation, and fabrication of shell structures. Simultaneously, we are in a position to address problems that are more complex and multifaceted--both culturally and technically--than ever before. These factors have instigated what Marc Kushner, co-founder of design studio HQKN and popular architecture website Architizer identifies as the age of experimentalism (Kushner, 2005, online). Often, this produces complex free-form projects that lack optimization or, alternatively, hyper-optimized projects that remove agency from the designer. Informing design through material characteristics provides an alternate way of thinking about the process and product of design while simultaneously informing the design process.

Our research contributes to this current discourse through the development of timber shell structures. We propose efficient structures made out of wood that provide a new solution to long span construction. Specifically, this essay will address the development of a doubly-curved CLT prototype from its initial conception to its physical production. The work presented describes a process of geometric rationalization and fabrication: this paper discusses the geometry, fabrication and the prototypes produced as part of our research. The first prototype is a doubly-curved panel that has the same radius in both directions; panels, if combined, produce a spherical dome.

[1] Associate Professor, School of Architecture and Landscape Architecture, Department of Applied Science, Associate Chair of Wood Building Design and Construction, University of British Columbia.
[2] School of Architecture and Landscape Architecture, Department of Applied Science, University of British Columbia.
[3] Assistant Professor, School of Architecture and Landscape Architecture, Department of Applied Science, University of British Columbia.
[4] Departments of Wood and Civil Engineering, University of British Columbia.
[5] Assistant Professor, Departments of Wood Science and Civil Engineering, Associate Chair of Wood Building Design and Construction, University of British Columbia.

The second prototype utilizes a variable radius, one in each direction. The success of these panels implies that this approach can be used for a large range of both pre-rationalized and post-rationalized geometric shell structures.

Culture, and with that the culture of building, is illustrated by how we construct. As Antoine Picon suggests in *Digital Fabrication in Architecture, Engineering and Construction:* "Culture … appears to a large extent dependent upon the way we make things" and "the relationship between thinking and making is at the core of culture". The computer's "impact has proved to be pronounced … on the processes that enable the production of artifacts" (Picon, 2014, p.V-VI). How we build and a how we, beyond that, explore available materials is a cultural aspect. "Technology does not develop in isolation from its cultural context; it emerges out of a process of differentiation with all its associated social, political and economic interactions" (Gramazio, Kohler and Wittmann, 2014, p.383). Building today needs to take advantage of available technologies and material understandings "to convert our built environment into civilization" (Schlaich. 2014, p.X). The TimberShell research is about building as cultural expression. Today, we can construct in structurally innovative, materially efficient and sustainable ways due to available fabrication technologies that were difficult to imagine previously.

Beyond understanding the qualities of structural engineering in design, this research illustrates the benefits of inter-disciplinary collaborations. Structural understanding informs spatial ideas and vice versa. The research views "structure as a mainstream architectural element rather than as a secondary element originating from the often self-contained 'structures' discipline of schools of architecture" (Charleson, 2015, p.228). Structural research is a significant part of the design discourse on spaces. Consequently, structural concerns play an important and guiding role in the design process of TimberShell.

2.0 Material computation

The freedom afforded to architects by new digital tools creates a condition in which almost anything can be imagined. Technologies also facilitate the understanding of materials in great detail and under multiple specific complex loading conditions. In this case, material characteristics and limits provide information for generating new designs based on material behavior. This approach to design, termed 'Material Computation' by Achim Menges, posits that material can be generative in design and inform the design process (Menges, 2008). TimberShell takes on this approach, in particular, looking to the bending capability of wood to facilitate fabrication of curved forms. Wood performs well in bending because a tree is designed to flex but to remain strong under wind loading conditions: it is designed to have strength and flexibility along its primary grain direction. The understanding of the ability of wood to bend and the conditions under which it remains elastic provides the basis of this project's ability to form a curve. With an understanding of the geometry of the aggregated wood pieces as well as an understanding about their ability to curve as single elements and to remain stiff as aggregate panels, we can engineer a structure that flexes into the desired curved shape and that is assembled into a sufficiently redundant and appropriate geometry to resist required loads.

3.0 Shell structures

Architects in recent years have shown a renewed interest in surface structures (Bechthold, 2009, p.9). This interest can be traced to the development of free form geometric modeling capability in architectural software and form finding relaxation methods, which are now pervasive in parametric tools available to designers. On the other hand, it can also be understood as a desire for these structures, which have been important designs since Roman times. It is only once the era of the mass-produced product emerged that the simple shell structure disappeared. Even with mass-produced products available, the experimental structures of Pier Luigi Nervi, Felix Candela and Frei Otto included many compelling shell structures. Their designs combine architecture and engineering knowledge. Recently, there have been alternatives on the form-varying support and boundary conditions have been experimented with to create a series of more complex spatial arrangements. This research responds to the desire for such structures with the proposition that wood is a material with which monocoque shell structures can be fabricated. Wood has the ability to be easily machined as well as the capacity to bend. It is a renewable resource and can be recycled as cellulose, lignin and other products for the relatively new bio-economy. The developed prototypes of the presented study are double curved and can take tension or compression. The stress is carried primarily in-plane. As such, any variation of the global geometries has to be generated to be close to a funicular form.

4.0 Inter-Disciplinarity

This research is based on a digital continuum; from design to fabrication (Kolarevic and Klinger, 2008). As Branko Kolarevic notes, it is the process based on modification that is more significant than formal change in the digital-based designs that are emerging today. The seamless collaborative process between architectural design, structural engineering and fabrication is facilitated by the digital flow of information between parties. "It is the digitally-based convergence of representation…"--and with that design processes--"…and production processes that represent the most important opportunity for the profound transformation of the profession" (Kolarevic, 2005, p.7), he suggests. The TimberShell projects described in this essay illustrates opportunities but also the work involved in participating in the design and building conditions brought about by digital media and fabrication. Among other issues, it has been stated that the integration of tools and process brings the architect back to the 'master builder' role--a role that requires that the designers have an in-depth understanding of the materials, tools and details of construction.

Shell structures are based on a relationship between geometry and performance. Historically shell design and construction, despite its inherent efficiencies, have been limited by computational challenges; not only is finding viable geometries to satisfy equilibrium difficult, but translating complex forms into algorithms for numerical analysis with analog techniques can prove impossible. The advent of 3D Nurbs modeling software, such as Rhinoceros, not only automatically construct such algorithms, but provide a parametric platform that can be integrated with structural analysis software for optimization. Our research incorporates structural design criteria such as connection or material properties into form generating scripts. This flow of geometry and data between generative, analytic and fabrication tools requires an approach where the boundaries between the three are such that geometric data can flow between them. This applies both to software and disciplinary knowledge.

TimberSkin is a joint research project between the departments of Wood Science and Civil Engineering and the School of Architecture at the (blinded for review). In addition, the project involves the (blinded for review), a research facility that supports research in wood and also acts as a liaison with industrial end users in (blinded for review). The project takes a multi-disciplinary approach where everyone on the team has specialties based on their background but no particular disciplinary restriction. The student teams worked together in the same space so as to facilitate close interaction. The project relies on engineering research to define specific limits, provide technical calculation on materials as well as help develop the iterative software that allows life feeds between Grasshopper in Rhinoceros and ROBOT Structural Analysis Software. Because of the scale of the project, the work could not be completed in the architecture facilities alone. As a result was built with the machinery and in the spaces of (blinded for review).

5.0 Material Processes

This project demonstrates the feasibility of fabricating thin full-scale shell structures from wood in order to demonstrate an expanded vocabulary in current architecture. To make a curved structure from wood, either an additive or a subtractive process can be taken. To avoid extensive wood waste from a subtractive process this project utilizes an additive process.

The ability to curve wood through an additive process relies on the wood's ability to bend. An understanding of the material behavior of wood becomes critical. It is possible to bend wood but only up to a point in order to not exceed the elastic limit and to maintain the material's load carrying characteristics. During prior decades, glulam or grid-shells have been bend and used in many structures. Recently, this process has been explored by Achim Menges group at the Institute of Computational Design (ICD) at Stuttgart University in Germany (Menges and Krieg, 2015, online). To bend wood further, its resistance must be reduced. Its depth can be reduced by cutting with the grain direction as a critical aspect of this process. In order to increase its strength after cutting it is possible to re-assemble wood elements by gluing them back together after they are bent. This increases the strength as well as helps to maintain shape. Thus the curvature of a wood shell can be 'tuned' by changing the depths of the laminations. As laminations become thinner, the curvature allowed under elastic bending becomes smaller. Using the natural bending curvature of the wood, we can determine what the tightest allowable radius for a building can be. The lamination depths can then be chosen for the type of building span that is required.

6.1 Fabrication Approach

The approach taken to fabricate a shell component looked at precedents of doubly-curved structures in wood. The barrel is a common wood structure used for generations. The staves of a barrel are tapered to facilitate double curvature; while the primary curvature is made possible by the natural bending properties of wood, the double curvature is accomplished by the stave's wider dimension in the middle and smaller dimensions at each end. In this way, the material is only required to bend in a singular direction but the aggregated pieces produce a double curvature

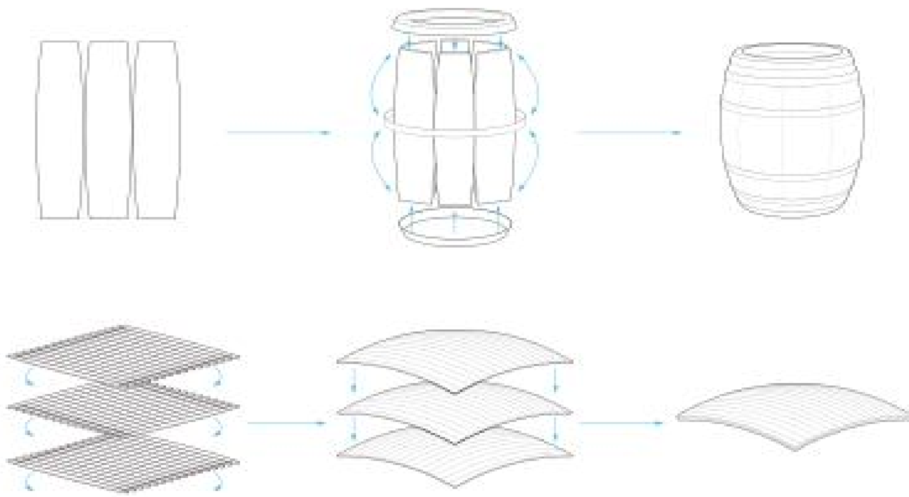

Figure 1: Geometric derivation of doubly curved fabrication

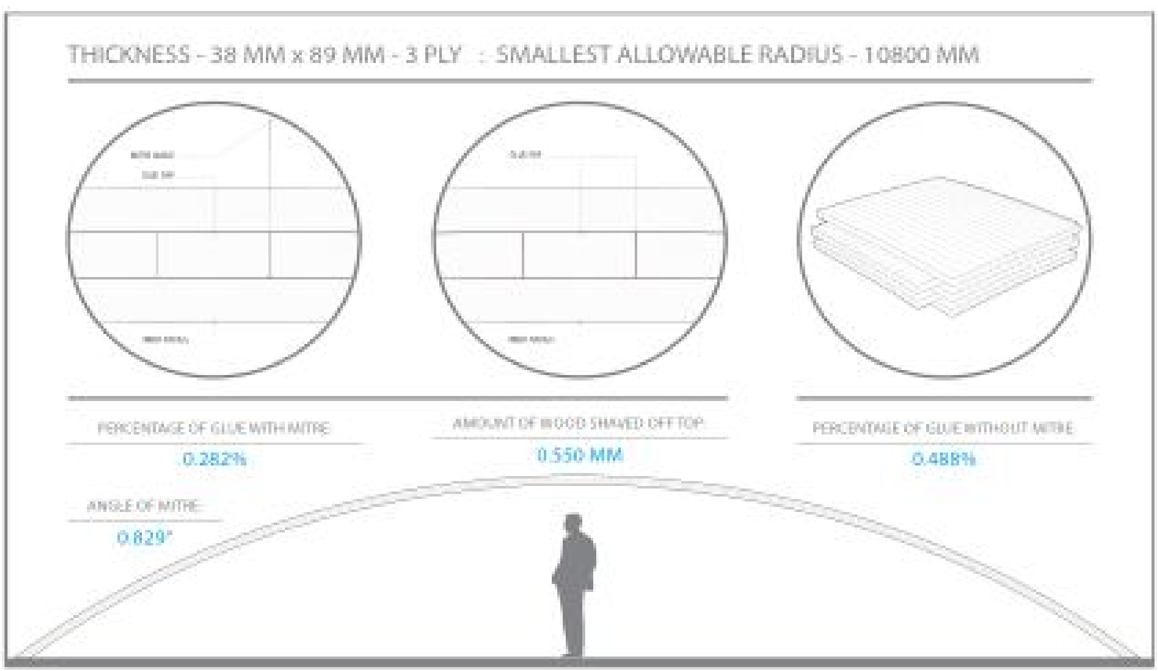

Figure 2: Material machining and fabrication considerations for 38 mm laminations (1)

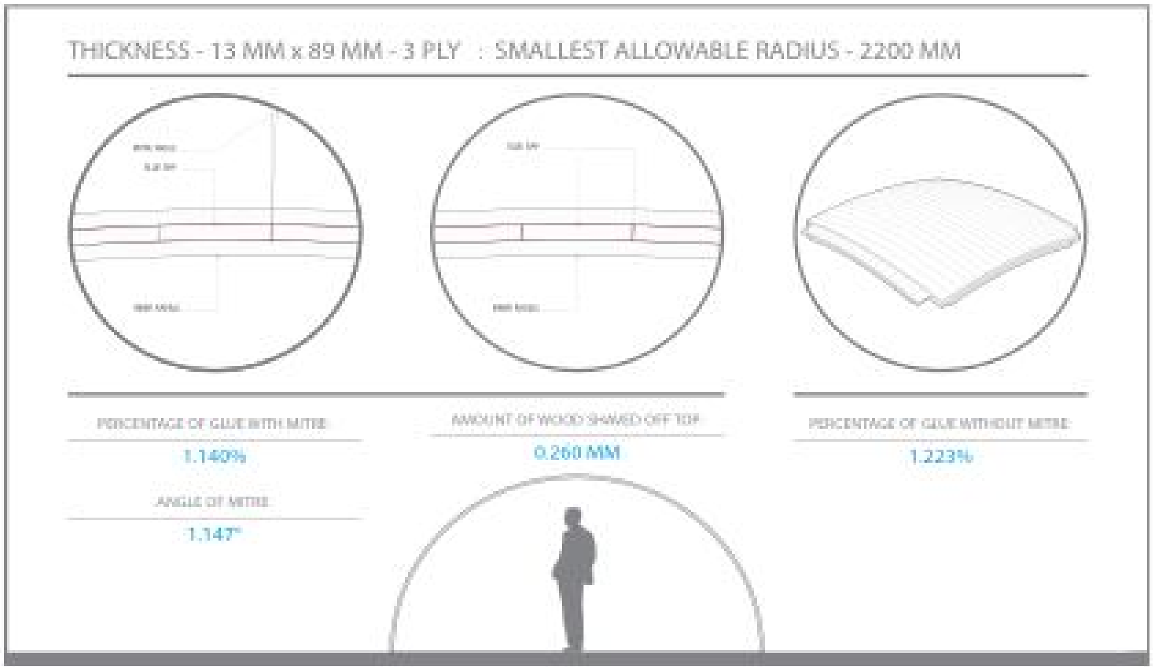

Figure 3: Material machining and fabrication considerations for 38 mm laminations (2)

Fabrication for the research can easily be done with a 3-axis CNC router but the question arose as to whether a 5-axis router would be required to properly shape laminations in the Z-direction (i.e. to miter the lathes). Figure 2 and 3 analyze the angle in the Z-direction between the panels to determine if this will contribute to significant glue wastage or produce a gap beyond the allowed dimensions by code. We determined that it would produce very negligible effects on the panels if we were to machine the sides of the planks but that it would require significantly more complexity in machining as a 5-axis router would be required.

Considerations of machine space are important to the feasibility of the fabrication of material at full scale by industry for a large project. The machine space of the available machinery in any lab will differ and thus the approach taken to a project may vary. This way available machinery feeds back directly into the design of a fabrication projects.

6.2 Geometries

The geometries of shells that were fabricated were intended as a proof of concepts. They illustrate that doubly-curved laminated shell structure can be fabricated and maintain their shape after fabrication. Equally, the research shows that a double curved laminated shell with different radii in opposing directions can be built and will maintain its form. The prototype studies prove this concept. It further holds that other geometries can be calculated and fabricated. The geometry of a uni-curved shell is a portion of a sphere; the geometry of a shell with different radii is a part of a torus. Single curved CLT panels have been fabricated the past. Figure 4 illustrates related geometries.

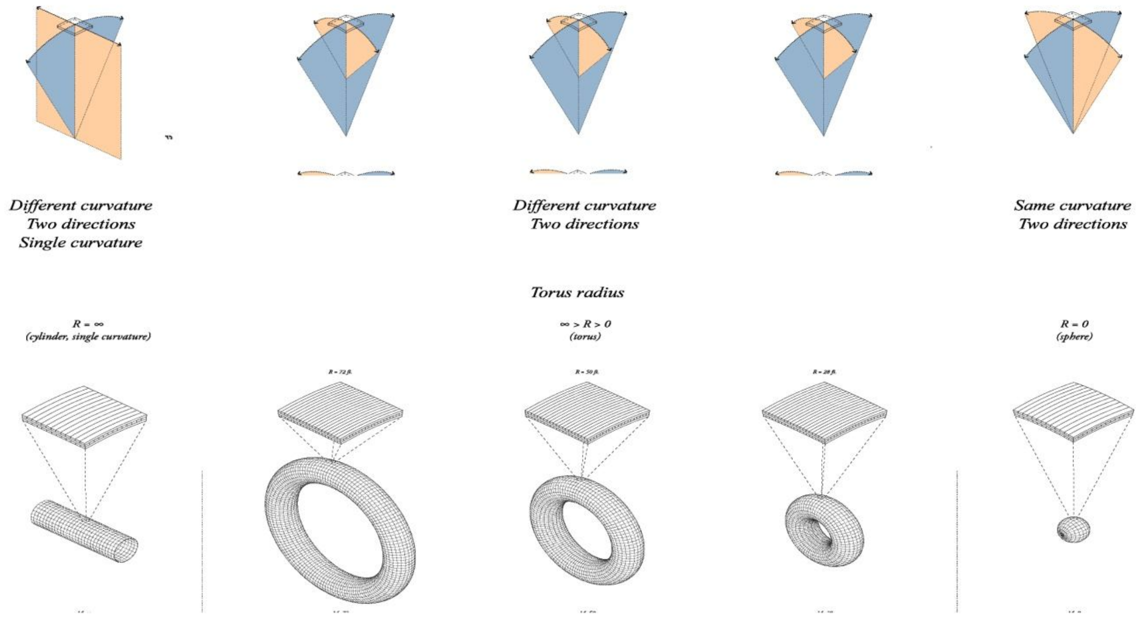

Figure 4: Geometries of fabricated prototypes

6.3 Prototype Properties

The first prototype (Figure 5) took the form of a 1.2 m x 1.2 m panel with the same radius in each direction (uni-curvature). We produced a 3-lamination panel with a series of 1 x 4 inch (2.54 cm x 10.16 cm) planks; the curvature of the radius was determined by the maximum bending capacity of the wood species used; in this case the project is bending vertical grain Douglas Fir with a 13 mm planed thickness at a 2200 mm radius. The prototype is shaped by a mold, and the first lamination is screwed down to establish a datum. The first prototype has laminations that were screwed together to establish proof of concept for the geometry. The next test panel is glued. The second prototype maintained its curved geometry significantly better than the first test whose radius 'bounced back. '

Figure 5: Fabrication of glued prototype with same curvature in two directions

The second prototype (Figure 6) took the form of a 1.2 m x 2.4 m panel with different radii in each direction. We produced a 3-lamination panel with a series of 1 inch x 4 inch (2.54 cm x 10.16 cm) planks; the curvature of the radius was determined by the maximum bending of the wood species used. Again, we are bending vertical grain Douglas Fir with a planed thickness of 13 mm at a 2200 mm radius in the short direction and a 4400 mm radius in the long direction. The glued prototype is shaped by a mold; the first lamination, however, was screwed down to establish the datum. This prototype maintained its curved geometry. To get a better measure of accuracy of the fabrication we are planning detailed scans of the prototypes to compare the resulting panel to the mold geometry.

Figure 6: Fabrication of torus shaped element

7.0 Conclusion

TimberShell demonstrates the feasibility of constructing curved laminated wood shell structures. The research is only a small step in the investigations required to realize a similar structures. Areas of future investigations identified include both material research and geometric research. Material research includes studies on designing and manufacturing joints between panels and a deflection prediction model for anticipating rebound deflections so that global geometries can be predicted. As well, a strength analysis is necessary in order to test the effective strength of shells relative to the fabrication method. Further geometric research includes design of component geometries for panels with inflection points and varying radii (such as parabolic shapes). In addition, production processes require research in order to increase the speed of production and to reduce the manual labor that is currently necessary.

TimberShell challenges the conception of wood as it is currently used and asks architects and researchers to experiment further with this sustainable and renewable material. The research indicates the potential of wood to be used as a structural and space-shaping material in designs that would traditionally use other building materials and methods. Our work shows that the ability to create novel forms and structures has outpaced our capacity to realize these forms with the materials we conventionally use. In addition, the studies indicate the significance of changing structural considerations from assumptions of stiff and often big and thick materials to notion of flexibility. The capacities of wood to flex and create curved forms as well as its machinability make it an ideal material for realizing the new experimental forms of architecture today. The research project also shows that “the application of digital technologies is no longer limited to design; it becomes operative for construction” (Gramazio, Kohler and Willmann, 2014, p.16). With this, design concerns are not separate from how we build.

Locality matters for the application of the research results as building code as well as material availability and quality are specific to regions. Despite digital media applications that are placeless and structural knowledge, design interventions are specific to place. As Stan Allen suggests, one needs to "learn from the complex self-regulating orders already present" (Allen, 2003, p.16) at a location to intervene architecturally consistent with a context. Structural and spatial interventions need to explore and understand local conditions and materials available such as wood types and locally sourcable wood building materials. Available technology plays a significant role in the design and building at a particular location.

In general, the described research focuses on explorations of structural capacity, efficiency and sustainability of wood. The explorations benefit from the blurring of disciplinary boundaries. They show that disciplinary collaborations result in new spatial and structural ideas. Architecture and engineering combine to generate new ways of looking at the potential of a common building material for spatial creation. Traditional material concerns and structures are revisited to introduce new ways of exploring material for design solutions that are efficient and sustainable. New software applications allow for the testing of solutions that would not have been possible previously; the combining of knowledge allow for materially-efficient and environmentally-friendly uses of a traditional building materials to create spaces central to building today.

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