Extending the Perception of Wood

Research in Large Scale Surface Structures in Wood

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Architects have a renewed interest in surface structures and the renewable resource of wood, along with advanced digital design, analysis and machining techniques, offers a way of manifesting these forms. Wood is easily machined and has bending properties that lead to the ability to form curves. This paper looks at the properties of wood, informing design through its material characteristics. The research presented here contributes to this discourse through the development of large scale timber shell structures. We propose hyper efficient structures made out of laminated wood products to provide a new solution to long span construction while satisfying the demand for agency in form generation.

Keywords: Parametrics, Surface structures, Wood design, Form finding

INTRODUCTION

The architect’s fascination with surface structures dates back to time immemorial, though the domes and vaults of the Gothic and Renaissance periods are some of the most admired examples. These systems combine aesthetic desire and utilitarian necessity by concurrently performing structural, expressive, and material operations. As scientific knowledge and modeling methods have advanced over the last century, domes, vaults, and variations on these systems have become simultaneously more refined and increasingly complex. This progression is illustrated by the extension of techniques and technologies utilized in Gaudi’s Sagrada Familia, Saarinen’s TWA Terminal, and finally Toyo Ito’s Funeral Hall. Given emerging technologies and advancements in engineered wood products, timber has the potential to be manipulated into systems that facilitate curved and irregular forms, allowing wood to provide an alternative to its steel and concrete predecessors.

The research presented herein combines the geometric logic of surface structures with the sustainable benefits of wood construction to establish a new strategy for creating free-form, long span constructions. This project straddles the worlds of the digital and physical, the architect and the engineer, using each to inform the other through a co-rationalized approach (Maher). The research addresses a vocabulary of structural typologies through an interdisciplinary study of global geometries, and then the implicated local conditions of the building compo-
nents through detailed drawings, integrated parametric models, and physical timber prototypes. The work presented is used to identify productive areas of future research and to establish strategies for industry use of timber surface structures.

MEANS AND METHODS

Establishing Material Parameters
The freedom and degree of power afforded to architects by new digital tools facilitates an understanding of materials in greater detail. With this knowledge the material parameters, machining limitations, and natural behaviours provide information for generating new designs, an approach to design termed 'Material Computation' by Achim Menges. Our investigations take this logic and apply it to planar and non-planar applications of mass timber products.

At the initial stage of research it was established that all investigations would utilize laminated engineered wood products: glulam, cross-laminated timber (CLT), laminated veneer lumber (LVL), and plywood are all examples of this. CLT and plywood panels are characterized by alternating laminations of wood which provide high bi-axial in-plane strength and shear resistance. As such, these panels are analogous to a precast concrete slab and have similar design potential. Nevertheless, while orthotropic materials like timber have complex behaviour, CLT is even more so, due to its alternating laminations. As the material properties modeled are specific to the structural typology being applied, because each typology forces the panels to respond differently to loading conditions, the applicable material parameters will be discussed in following sections.

Establishing Structural Typologies
Following a survey of contemporary long span surface structures, we have focused on the following two typologies: folded plate structures (built from planar components) and continuous shell structures (built from components with a double curvature). These typologies, largely explored in concrete and/or steel construction previously, are explored as global geometries and as full scale building components. The global investigations, derived from structural analysis and material research, consider aesthetic, spatial, and structural implications of the timber proposal. The full scale building components are tested through detailed drawings and physical prototypes to determine the feasibility of the proposals as it relates to current industry standards and expectations.

(Equation 1)

Figure 1
Two surface structure typologies are identified for timber investigations

Evaluating Geometries: A Co-Rationalized Approach
Once the role of the classical architect was divided into two distinct bodies - the architect as aesthetician and the engineer as technician - disconnect between the sibling professions ensued to the detriment of each. Structure is essential to architecture, but relegated to a reactionary role, the structure must accommodate geometry which has been pre-rationalized without it. This disconnect makes the development of surface structures difficult; surface structures require a constant feedback loop between design intent, structural ramifications, and design development. Computational tools now enable both disciplines to perform at levels that were previously impossible, but a complete and iterative integration between the two fields has been slow to develop. Architectural and structural model integration would not only accelerate the design process but enable informed innovation. It has been the objective of this research to integrate these processes through a co-rationalized approach, in which the roles of the architect and the engineer blur, in order to evaluate the global geometries of the structural typologies presented here.

Rhinoceros (commonly referred to as Rhino) is a 3D modeling software that generates lines and
surfaces using NURBS algorithms. These algorithms originated in the aerospace and automotive industries as a means of conveying curved geometries to numerically-controlled fabrication machines which could be easily adjusted by changing algorithm coefficients and parameters. In contrast, the CAD software developed for building design were vector-based and intended only to simulate hand drafting: the numerical process by which lines were generated were kept hidden from the user.

Grasshopper, a Rhino plug-in, provides a visual programming language in which these NURBS algorithms and parameters are displayed as components and 'wired' together into generative networks, bypassing the drafting user interface altogether and permitting direct manipulation of these algorithms according to the designer's prerogative. 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. For the purposes of this project global geometries were evaluated through an automated iterative process between Grasshopper in Rhino and the Finite Element Modelling (FEM) software Robot Structural Analysis via the proprietary Grasshopper plugin Geometry Gym. This valuable plugin establishes a live feedback loop between architectural geometry and structural performance, not only providing rapid evaluation but also vividly illustrating those structural criteria which limit, and those which can be exploited further.

FOLDED PLATES: TIMBER SURFACE STRUCTURES FROM PLANAR COMPONENTS
The stunning spaces rendered with the use of folds 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 Merrill (1962) are in fact only simulacrum of surface structures approximated with trusses. In our research folded plate surface structures provide the stiffness of a truss without an artificial skin, but require close collaboration between architects and engineers to manifest, hence their candidacy for a co-rationalized design approach.

There are two major barriers between the implementation of folded plate structures and the building design industry. The primary issue is one of managing geometries; even with the advent of computer modeling, folded plate geometries are complex and difficult to modify. These geometries pose problems both to the architect - who needs to be able to quickly manipulate and iterate through geometries as constraints and programmatic requirements surface - and to the engineer, who needs to evaluate these geometries analytically. Difficulties related to sharing models between disciplines further complicated the matter. The second issue is one of construction; there is an expectation that these complex geometries are onerous to fabricate, that difficult join designs are necessary, or that construction is exceedingly troublesome. In our evaluation of folded plate geometries we address these concerns using a combination of digital modeling and physical prototyping.

**Investigations of Global Geometries**
The initial step of this exploration was to establish a digital workflow for managing folded plate structures that facilitates a co-rationalized approach. This problem is two-fold: the workflow must allow for easy management and manipulation of plate geometry while also simultaneously implicating the structural ramifications of design changes. In early studies geometric explorations were perused in Rhino via Grasshopper that gradually increased in complexity. The parametric nature of these explorations begin to build a platform for design management that has previously been lacking.

The initial explorations were organized into two typologies: parallel and diagonal folds. Within each of these categories, flat walled and folded wall options were explored. In our next exploration the Grasshopper models were expanded to apply the
fold logic to a single surface (the intended global geometry), in which the number of pleats generated in both the x and y direction can be reduced or increased per the design teams intent. This model was then linked with an FEM software so that the system could automatically increase or decrease the depth of the pleat fold based on the structural necessities of the global geometry. (Fig. 2)

Once the fold was linked to the global geometry and to the resulting structural depth, a series of openings and fenestrations were applied. The algorithms used in this process take into account the structural analysis of the global geometry and generate a pattern of openings based on local conditions. In the studies shown, openings were incorporated in the centres or corners of the panels. (Fig. 3, Fig. 4)

Through these preliminary studies, an integration of Rhino, Grasshopper, and FEM software was accomplished and a co-rationalised design approach established that would facilitate the management and manipulation of geometry. This provides a possible platform for future design teams, consisting of designers and engineers alike, to design with and evaluate folded plate structures.

**Material Specifics**

If an orthotropic material like timber is akin to a bundle of straws, then CLT is like a woven mat, and is often modeled in engineering literature as small structure in itself. It is not enough to assume generic timber qualities for a whole panel: cut at angles, the panel will sag slightly, like a textile. Unfortunately engineering design guides provide no guidance for extraordinary geometries, nor is there widely available experimental data on the same for reference.

Hence, to establish the theoretical structural behaviour of a folded CLT plate, material equations describing properties of individual laths (Hankinson), lath layers and the panel as a whole (Gagnon) (Fellmoser) were combined and then written into a custom Grasshopper using the coding language Python. This component, along with additional structural design criteria (CSA O86-09, 2010), were integrated with a Grasshopper script which morphed the geometry of an individual panel into different shapes and orientations, effectively creating a simulated testing space. The link with Robot provided structural responses for a band of angles and shapes, thereby identifying the worst case loading angle condition: about 75° to the exterior layers, rather than 90° as stated in most guidelines. It is this value which was used as the ma-
terial property for all subsequent folded plate iterations.

This was a conservative assumption, yet preliminary simulated test panels with the geometry of the folded panel elements satisfied performance criteria for deflection. Additionally, the integrated Grasshopper model was used to study the structural response to geometric morphologies and mutations. In this manner we developed guidelines for permissible bands of lamination orientations, panel dimensions, fold angles, and spans.

**Testing the Local Condition**

The benefit of the folded plate typology when considering the use of mass timber is that the local components are inherently planar; this reduces the modifications necessary to standard products available to the industry today. However, an investigation into the limitations of this system at the local scale is pivotal to the discussion of folded plates as a feasible typology. This investigation considers primarily fabrication issues, as well as the implications of structural connection detailing.

In addition to playing a central role in aesthetics and assembly, joint design is critical to both local and global structural behaviour. Structural joint design imposes geometric limitations, varying with connection type and design code, a process which has significant ramifications for the generation of complex architectural forms; that is, in the case of folded wall assemblies, minimum member dimensions and angles are limited by connection spacing requirements. Different systems also provide different degrees of load and moment transfer, ease of installation and disassembly, and versatility. Several connection systems were considered, including glued-in plates and interlocking clips, but their application was restricted by the additional manufacturing requirements of the former and the geometric limitations of the latter. Self-tapping wood screws are not only easy to insert but also to procure, provide a high-capacity connection, and hence were the fastener of choice in this design.

A Grasshopper model integrated with Robot was also used to develop the connection schedule for self-tapping screws. An algorithm was scripted which dissected meeting edges according to spacing requirements for self-tapping screws (ETA-11/0190) and then isolated different connection points according to a variable frequency. As each pair of crossed screw connections had a known unit capacity, the frequency of connections along each seam could be tuned to satisfy design loads. This tuning process was done using Galapagos, a genetic solver optimization component which automates iterative analysis for any black-box function with a target value.

**Fabrication of a Prototype**

(Fig. 5)

Following our study of the material and joint design implications of a CLT folded plate system, a prototype was constructed to test our hypothesis of machine and assembly constraints. Because our primary interest was to test the fabrication process, Russian Birch Plywood was used in substitution for CLT. Though smaller, plywood has bi-directional properties akin to CLT and furthermore reduced the scale to be within physical perception, a quality which in a digital age should not be underappreciated. A series of rationalizations took place to account for the standard panel size and thicknesses of Russian Birch Plywood; the prototype would need to facilitate the efficient use of 4'x8' panels.

A material thickness of 1 ½" was required to accommodate the self-tapping screws without splitting the member. While butt joints, finger joints, and mitered joints were all studied through detailed drawings, a mitered joint allows for knife edge detailing, emphasizing the thin seam of the fold, while pairs of crossed screws can pass through the mitered edge symmetrically, improving the structural rigidity of the wall. The angle of the fold was further rationalized to accommodate the thickness of the material while facilitating the constraints of machine space. Based on the facilities available to our research, we used a ¾" drill bit on a 5-axis CNC which limited the
depth of the cut to 3½". The angle of the fold also had to consider the use of self-tapping screws; if the angle had been more acute, the amount of material available to support the screw heads would have been insufficient to prevent the fasteners from tearing out. Based on these constraints a 7'-0" tall wall with a 63° partial Yoshimura (anti-prism) origami fold (Buri) was proposed to be built from 1½" furniture grade plywood with a mitered joint, connected by self-tapping screws. Using the automated algorithm described in the previous section, it was determined only three cross-pairs of screws were necessary along each seam.

Once the geometry of the prototype was established, the process of machining and assembly could be tested. First, two sheets of ¾" plywood were laminated together to create the 1 ½" panel thickness specified. Due to the edge condition of each triangular component, each piece needed to be machined individually. To facilitate this, each panel was cut in half while maintaining a calculated origin for the second stage of machining. From there each piece was machined on the 5-axis CNC and the fastener locations were pre-drilled and countersunk to facilitate accurate assembly. Because each screw was oriented perpendicular to the panel it was crossing into, and not perpendicular to the facing panel, pre-machining these angles was imperative. Additionally, as there were only four component types to fabricate (two sets of mirrored triangular pieces), circular markers were used to indicate if the panel was a type I, II, III, or IV. Once machined each component was quickly sanded with an orbital sander, with attention to cleaning up any tearing along the mitered edges.

Following the machining and finishing of the components, the assembly was straightforward. The components that established the base structure were fabricated in pairs first as they could simply sit on their flat edge and be easily fastened. The top pieces were lifted and held individually and fastened to the base pieces. Within a few hours the wall was built.
The prototype established that with appropriate tools to manage and manipulate the primary geometries of folded plate structures, the machining and fabrication process can be easily facilitated. Automated machining with a CNC allows the burden of complex geometries to be machined with ease and accuracy. Many of the limitations we ran into were specific to our facilities and could be eliminated in future studies. For example, the depth of the cut along the seam was limited to 3½" based on our machine constraints; however, with the use of a wider bit or a saw function, a deeper cut could be facilitated (which would be imperative to larger scale studies with true CLT panels). Future prototypes would pursue testing the implications of true CLT panels in a folded plate application as well as facilitating irregular folds, a spanning condition, and the application of a building envelope to the structural system.

CONTINUOUS SHELL STRUCTURES: TIMBER SURFACE STRUCTURES FROM DOUBLY-CURVED CLT

The second structural typology investigated in this research is continuous timber shell structures. While the folded plate system assumes the desire to use wood as a planar material, a continuous shell structure tests the merit of that assumption by relying on the bending capacity of wood to facilitate the fabrication of curved forms. As this typology utilizes a structural shell in its pure funicular form, the study of the global geometry was not the challenge. Rather local geometries and physical prototypes were the focus of this investigation.

Material Specifics

The challenge of continuous shell structures is establishing a double curvature. Constructing a double curvature from a planar material is impossible without cutting, bending, and reconstructing the sheet; for this reason the majority of precedent continuous shell structures are constructed from cast-in-place concrete, yet this does not necessarily mean timber cannot achieve such forms. Fabricating a double curved CLT panel, as opposed to milling a curving surface from a larger planar panels, sidesteps the waste and structural issues associated with attempting the latter.

Owing to their natural flexibility, timber lathes may be forced into curves, so long as the elastic limit of the wood is not exceeded; the thinner the lath the tighter the curve which can be produced. A continuous shell can be very thin: condensed into laths, the depth required of the linear member to carry the design loads would cause the lath to rupture before achieving the desired curve. This issue has been overcome in timber gridshell projects of note in both architectural and structural discourses. First pioneered by Frei Otto and Arup for the Mannheim Multihalle (Happold), such research and design has been continued by Shigeru Ban and Edward Cullinan in conjunction with Buro Happold (Naicu). These shells use thin individual laths to permit more severe curvatures; once bent, multiple laths are bolted together so that in composite they provide sufficient strength.

Consider now that curved glulams are fabricated by clamping the laminations in place until the adhesive has cured. In our own work we have taken the double-layer composite lath strategy used for timber gridshells and applied to the layered fabrication process of an individual double curved CLT panel. By constructing the panel out of a series of strips each plank is only required to bend in one direction while the double curvature is established by the slight facet from strip to strip and the gaps produced between the planks.

Attaining a Double Curvature: Investigations in Geometry

Single curvature CLT panels are available in Europe, though rarely produced, while double curvature CLT panels have no contemporary precedent for reference. Instead, historic precedents can be found, not in architecture, but in late 19th and early 20th century water main and sewer designs, which in forested areas were built with large timber tubes made from tightly jointed laths. These likely had lin-
eage from the much older shipwright and cooper (barrel-making) industries. Barrels making techniques, which use tapered laths called staves to produce double-curvature, provided the baseline geometric logic for double curved CLT panels. (Fig. 6, Fig. 7)

While cross lamination only necessitates that each plank bend in one direction, straight pieces arrayed about a curve would produce gaps between the boards at the edges of the panel. These gaps would exceed the 3mm limit prescribed by the European Technical Approval for CLT (ETA-14/0349). In order to account for this disparity the tapering techniques utilized by traditional coopers were applied to the laths of each layer. In our application the resulting staves, widest in the middle and thinnest at each end, compensate for the double curvature and minimize the glue gap between the planks.

With the lath geometry defined, two types of continuous shell structures were investigated for the purposes of this research: a constant shell with a singular radius in both directions (a sphere), and a shell with variable radius (a toroid). In each case the global geometry was panelized into rectangular components. From the rectangular surface established by the global geometry a custom doubly-curved cross laminated panel was created.

As with the folded CLT plate assembly, the global geometry is directly related to the local condition. A series of drawings were produced to illustrate the relationship between the thickness of the wood laths, the number of laminations, and the maximum curvature possible for the local and global geometries. While the thickness of individual laths was based on glulam curvature limits for softwood (CSA O86-2010), the number of laminations, and thus total panel thickness, was rationalized to accommodate potential connection systems. The interior layer of laths were staggered to create slots for jointing with other curved panels, via either complimentary finger joints or interior splines fixed with self-tapping wood screws. (Fig. 8)
**Fabrication Prototypes**  
(Fig. 9)

Following the production of digital models to test the geometric exploration described above, two prototypes were constructed as proof of concept. As with the folded plate typology, it was necessary to test the process of machining and assembly to see if the geometric hypothesis could manifest in the physical world and to see what the implications of fabrication would be for such an unprecedented construction.

Douglas Fir was chosen as the material for the panel as it allows for a direct comparison to regional CLT manufacturing standards. In order to minimize material waste and to optimize the fabrication process for standard lumber dimensions, the prototype was designed for 1"x4" planks. At this stage of research, two prototypes have been constructed; the first (Prototype I) with a singular radius in both directions and the second (Prototype II) with a variable radius.

The first step to developing the prototype was to build a jig that could establish the position of the curvature relative to the planks; the pieces would be assembled on top of the formwork and the constructed panel would be removed following assembly. The 5-axis CNC at our facility provides 11" of vertical machine space; this dimension was used to establish the maximum curvature possible for a 4'-0" wide prototype (the width of the prototype was established by available machine space in the horizontal axis and by the standard width of MDF panels which would be used in the construction of the formwork). Based on machine constraints, the maximum curvature for the singular radius prototype (Prototype 1) was 8'-4". In order to test the maximum bending capacity of the material while fulfilling the softwood curvature guidelines, the planks were planed down to a ½" thickness. The jig was then finished with bumpers along two facing edges. These bumpers allowed for the bottom lamination to be temporarily fastened into place so that the second and third laminations could be glued on top of them. By making these bumpers removable we could ensure the use of this jig for as many prototypes as might be desired for future investigations.

Each lamination consisted of two plank types; the edge planks differed from the interior planks in order to create the square prototype desired. This resulted in six plank types per prototype: two types per...
lamination, with each lamination differing slightly in length and profile. The planks were then machined on the CNC (a 3-axis CNC would be capable of this, though a 5-axis was used in our case), and set aside for assembly. It should be noted that the planks for the bottom lamination were designed with sacrificial tabs for fixing the base lamination to the jig. (Fig. 10)

The panels were assembled in two stages. The first two laminations could be assembled in the same session; the first lamination is temporarily fastened to the bumpers of the formwork and the second lamination is adhered to the first lamination. In order to simulate the production of standard CLT panels, a PVA adhesive (commonly known as carpenter’s glue) was used to laminate the planks together. The first plank was positioned based on the centerline of the formwork and each successive plank was fixed on either side in a symmetric fashion toward the edges of the jig. The bending capacity of the plank allowed the pieces to be pushed to the formwork by hand and to be temporarily fastened (in the case of the base layer) or temporarily clamped (for all successive layers) while the adhesive set. After 24 hours the clamps of the second lamination were removed and the third lamination could be applied, following the same logic stated above.

Prototype II tested the feasibility of a toroid form, this results in a variable radius panel. While the methods of fabrication mimicked Prototype I, the geometry differed. The jig constructed for this exploration used the same maximum curvature in the short direction (an 8'-4" radius along a 4'-0" prototype) and based on a 2:1 proportion utilized a 16'-8" radius along an 8'-0" edge in the long dimension. The top and bottom laminations would be oriented in the long direction while the middle planks were oriented in the short direction to maximize panel stability. (Fig. 11, Fig. 12)

Both Prototype I and Prototype II were successful in confirming the feasibility of a doubly-curved CLT panel using the logic of traditional coopering. While the process did require time for each glue lamination to set, the labor required was not excessive and an automated processes could be established if the system were to be implemented at a large scale. In addition to the cost of time (necessary for machining the components and assembling the panel), a small amount of “bounce back” was seen in both proto-
In future investigations this dynamic would need to be measured and anticipated for future assemblies.

FUTURE RESEARCH FOR TIMBER SURFACE STRUCTURES
The two structural typologies investigated here demonstrate the feasibility of constructing long-span timber surface structures. The work presented is only a small step in the research required to realize these systems at a full scale. Areas of future research identified include both architectural and structural topics. The design and manufacture of innovative connections between panels, specifically furniture-type interlocking clips and those combining adhesive with traditional joinery techniques, warrant investigation to provide a means of easy installation of rigid connections applicable to a variety of geometries and simple erection methods. Developing more detailed integrated models which anticipate rebound deflections are needed to produce more predictable global geometries. A structural test regimen on both angle-cut and curved CLT panels would also provide much needed empirical data for future designs.

CONCLUSION
This co-rationalized research expands the vocabulary of wood architecture and challenges architects, engineers, and researchers alike to experiment further with this sustainable material and new design tools. Developments in technology have outpaced our ability to realize these forms. The natural properties of timber, combined with its machinability and ongoing advances in computational design, make it an ideal material for realizing the digitally facilitated experimental forms of current architecture.

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