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Beyond Form Definition

Material informed digital fabrication in timber construction

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Abstract: This paper introduces a series of prototypes investigating a new architectural language in wood that is driven by a critical approach to recent technical developments in design, fabrication and material. Although wood is slowly being recognized as an advanced material for future construction due to its high performance and sustainable nature, its differentiated and unpredictable material characteristics have not only been progressively overlooked, but even been viewed as a negative attribute. Wood's varied dimensional range has been addressed through standardization, its heterogeneous fiber structure ground and reconstituted into homogeneous composites, and finally its complex aesthetic quality has even been caricaturized into a skin-deep plastic-wood veneer texture. This paper seeks to extend research on the implications of advanced robotic fabrication and its integration into design processes that also integrate cross-disciplinary knowledge into architectural software. As innovation in technology enables architects and engineers to engage with the complexities of the material, the potential of wood is becoming accessible, leading to a new material language. Through a series of full scale, robotically fabricated design prototypes, the material performance of wood is investigated as a driver for form; its fabrication and hygroscopic performance as a driver for assembly, and more importantly, the entire design-to-fabrication-process as a method for investigation into innovation and the structural and architectural potential of future wood.

Keywords: "Robotic Fabrication, Computational Design, Material Computation, Elastic Bending, Timber Structures, Complex Surfaces, Wood Joints"

Figure 1: Timber Wave prototype, doubly curved timber assembly, at the University of British Columbia Campus.

1. Introduction

Innovation in material results in innovation in architecture. Technology both supports the development of new materials, and changes how we use traditional ones. In parallel, these innovations bring about a change in how the building is made, and in many cases, how the building is designed and conceived.

Developments in steel manufacturing, for example, revolutionized building construction in the 19th Century – its strength increased significantly with new smelting technologies and it, along with advances in elevator technology, freed the building from load bearing walls and allowed new forms such as high-rise buildings. Reinforced concrete allowed for a similar revolution in the 20th century – it was malleable, could take tension and allowed new forms to be built due to the casting process. Designers such as Maillard, Nervi, Fisac, Corbusier, Eero Saarinen, and Oscar Niemeyer took advantage of this material innovation and were foundational in creating a new architectural language for the time, which engaged the properties of the material and the innovations of the construction process – clean, curved, large scale structural forms – a language recognized as representing contemporary design in the mid-1900s.

Steel today is produced either as linear or sheet elements and requires a significant amount of energy in the manufacturing process (Gordon, 2003). Likewise, concrete is very energy intensive (Gordon, 2003) and very heavy – the weight of concrete as dead load is often equivalent to the live load it can support. With the building industry being one of the biggest sources of Green House Gas emissions (COM, 2014), sustainable building materials and building techniques are most important for a sustainable future. Especially in developing countries, where not only the production of materials but also the production of energy itself poses an ecological challenge, pollution by the construction industry has become a serious problem. As such, these now common materials, while often giving yield to innovation in the past, face new economic and environmental challenges that question their long-term feasibility.

If we were to put forward the criteria of the material of the future from the viewpoint that we hold today, we would require it to be sustainable, lightweight, structural, multifunctional, compelling, and receptive to the new parametrically driven forms that are enabled by digital design. The material, answering to many of these criteria, is wood. Wood can perform in tension as well as compression due to its natural fiber structure. It can be employed as structure, finish or furniture and as a final attribute, it is generally considered aesthetically pleasing because of its organic grain and depth of tone and color. In its natural occurrence wood already exhibits high structural strength, a positive carbon footprint (Kolb 2008), and very low embodied energy (Alcorn 1996). Moreover, its local availability in moderate climate zones makes the material particularly suitable for the development of more sustainable construction methods (Krieg et al 2015). It comes to no surprise that the general interest in wood architecture has grown over the last decade.

In the long history of architecture, wood plays an almost continuously dominant role as a building material. Buildings that still stand today showcase intricate construction systems made from posts and beams - the most famous of these being Japanese and Chinese traditional temples, although this type of construction can be observed in any civilization that had access to forests in their time. Structures made from linear elements required a large amount of material knowledge and technical skill to source and carve them, resulting in the emergence of extremely skilled craftsmen and a culture of wood fabrication that persisted until the early 1900s. A shift from local knowledge and local production to industrialization and mass production for a global economy also brought a shift from value-added products to value-engineered standardized components. This shift also precipitated a disciplinary change, from an integrated design-to-fabrication model based on the mastery of a craft to the split between design, engineering and manufacturing. In this new context, each step is subsequently compartmentalized into highly specialized but also further disconnected disciplinary domains; design is only concerned with form and function, engineering with material and manufacturing, management with production and supply chain, trades and operators with execution and assembly. Multiple hierarchies are conceptualized within this model, which limits the free movement of knowledge, expertise and ultimately hinders innovation.

Research on innovation has pointed out that the building industry is on par with other industries in terms of “incremental innovations”, which refers to minor changes in the product. However, the same research also points out that the building industry is a laggard adopter when it comes to “systemic innovations”, which refers to product and process innovations that require multiple and inter-dependent industries to change their processes (Taylor 2006, 16). Systemic innovation diffuses slowly in project-based industries such as in today’s construction industry (Taylor 2006, 9), as it requires multiple organizations acting together to implement the change; this is known as an interorganizational network (Taylor and Levitt 2005, 9). The reason for this is that “[w]hen organizational variety is high and the span of a systemic innovation increases to impact two or more specialist firms, extra coordination is required for inter-organizational knowledge to flow and accumulate” (Taylor and Levitt 2005, 15). Systemic innovations such as the one being discussed here - a major change in the conceptual approach to wood design – would thus require not only an innovation in the actual development of the technology but also a re-examination of the process of design and building in order to avoid the friction inherent in the conventional building industry of today.

Viewing this process in terms of the type of innovation – by use of Slaughter’s definitions of innovation - the types of innovations in these projects is radical in the form of the robotic fabrication process. Particularly, the direct integration of design input within the automation poses an entirely new model to the building industry. Slaughter states that a radical innovation is one which “creates a new way of understanding a phenomenon and formulating approaches through which to solve problems” and that “All previous linkages and interactions may be irrelevant for a radical innovation, not only with respect to the systems, but also the ties among organizations.” (Slaughter 1998, 227) Structural steel, she states, is considered a radical innovation because “a whole new industry of steel manufacturing and fabrication emerged, as well as new components and systems linked to the new structural forms and systems.” (Slaughter 1998, 228)

In these terms, then, the radical innovation of steel also affected the various organizations which create systemic innovation, because as mentioned, the construction industry is an interorganizational network. However, it was not considered systemic, possibly because the innovation was outside the system and not derived within the system. It is unclear whether the innovation described and anticipated by this paper would be considered radical or systemic – it could be systemic because, if implemented, it would likely be implemented by a partnership between architects, engineers and fabricators. Still, the industrial robot applied to the wood fabrication industry may be considered a radical innovation partly because of the implications of the ability to change the workflow – taking the fabrication control back to the design stage.

Winch has discussed the very slow innovation in the construction industry and describes the problem as follows: “First, the systems integrator role is shared between the principal architect/engineer and the principal contractor. Thus, construction typically has two separate systems integrators - one at the design stage and one at the construction stage. Secondly, the fragmentation of the professional bodies in construction has weakened their ability to act as honest brokers of innovations as they typically threaten the interests of one or other amongst them.” (Winch 1998, 270) “The development of separate and specialized design professions helped to bring about divergent interests between engineers and architects and the organization of design had no built-in mechanism to bring about innovation in the absence of external stimuli from clients or materials’ producers.” (Gann, David M. 2000, 43) One method of overcoming this inter-organizational friction is to adopt an organizational strategy of integration which would reduce “organizational variety” and increase the “capability to adopt and diffuse an innovation.”(Taylor and Levitt 2005, 9)

The process discussed in this paper operates under a “single system integrator”, as per Winch, both design and construction are considered under the same umbrella of execution, thereby reducing the systemic friction to innovation. By embedding design, engineering and rapid prototyping within the manufacturing floor a more horizontal exchange of information is made possible; an “Open-Source Workshop”, where multiple disciplinary sources of expertise are engaged. It is only through this type of “single integrator” framework that it may be possible to re-engage material informed fabrication and assembly techniques. Professional and academic outcomes of this type of approach are beginning to emerge more and more. Designers such as Shigeru Ban (Sunny Hills Desert Shop, Triangle House, Aspen Art Museum, Tamedia Headquarters in Zürich) and Kengo Kuma (Prosto Museum and Research Centre, Daizaifu Temanga Shrine Starbucks interior) have experimented with this integrated approach and have changed traditional wood fabrication into a much more expressive modern architecture. For example, traditional joints through digital and robotic fabrication, allow not only for the most intricate details, but also for the possibility to precisely orient building elements. More comprehensively, this type of systemic innovation across interorganizational networks has been demonstrated by the group of firms Design to Production in collaboration with Blumer Lehmann, and SJB Kempter Fitze (Antemann 2013) in order to realize complex projects by SANAA, UN Studio, Zaha Hadid, Shigeru Ban, and Renzo Piano. This process of decompartmentalization begins to open the door for a new and cross-sectionally informed design language to emerge.

2. Patterns of Innovation in Materials and their Consequences

By looking at patterns of innovation in materials in the past, it is possible to strengthen the argument that innovations in wood today have the potential to create a large change in architectural design and, in fact, in the building industry generally. As Antoine Picon has noted, "In the case of architecture and construction, as in many other areas of material culture, innovation comes about at the intersection of technical and social issues that need to be decoded." (Picon 2010, 51) This section will look at both what created the innovation in material and what changes therefore resulted in building processes. The argument presented here is that the innovation in material is concurrent and catalytic to other changes in the design and construction industries. The developed prototypes provide evidence of this shift, positioned at the intersection of technical, material and social developments. The projects offer an insight into a material revolution on a larger scale rather than simply an innovation in material.

2.1 Steel

The development and use of iron shows how the change in technology results in a change in design and form. When iron was first used in construction, its building elements and joints resembled those made from timber. Only once a better understanding of the differences in the material characteristics was established, joints and building elements moved from an imitation of timber construction to a more appropriate technique for iron, such as bolting and riveting, or cast lugs and flanges. (Peters 1996, 38) Secondly, "[t]he primacy of connection technology in iron changed the way designers thought about construction." Since iron has to be produced in a factory – it is a "process of *assembling* pre-fabricated components with prefabricated connectors" (Peters 1996, 42). This was a change in thinking about how construction was carried out, as previously materials were manufactured or easily worked into parts on site. This change was not instantaneous but took several decades to occur (Peters 1996, 42). Compared to the initially used plain iron, these changes became even more pronounced when wrought iron was developed, as it allowed a symmetrical cross section with equal flanges because of its equal strength in tension and compression. As the knowledge of iron-related construction was developing, engineers experienced the phenomenon of fatigue fracture in iron parts in mills. This observation and the following efforts into the chemical makeup of iron led into the development of the field of material science (Peters 1996, 44).

Steel further played a role in developing engineering as an academic field. Richard Turner, in designing the Kew Palm House, developed a methodology which "demonstrated that it was possible to fulfill contradictory criteria in a single detail by decoupling the problems, solving each on its own serially, and then reuniting the solutions to form a component subset in a construction system" (Peters 1996, 220). Turner's "clear hierarchy of structural members and their relationships advanced technological thought in building"(Peters 1996, 220). Like Turner, Gustav Eiffel segregated issues to solve the more complex problems; whereas Turner detailed the solutions to a specific building, Eiffel developed solutions which used an open system to build any iron structure (Peters 1996, 266). The Eiffel Tower and the Galerie des Machines at the 1889 Paris exhibition were demonstrations of this type of technological innovation, defining structural systems still being used today.

While pre-designed and pre-engineered steel structures shape every city today, both steel, and its predecessor iron, had to overcome significant uncertainties about its application in structures and architecture at the outset. This uncertainty was not only in how to approach its visual language but also in how to ascertain its structural requirements for configuration. Steel was high strength and little was needed relative to a stone or wood structure, but the question of its appearance and how to use it visually was a conundrum as it did not fit in with the predominance of historicism in architectural expression at the time (Rinke and Schwartz 2010b, 17) (Picon 2010, 52). The public did not generally consider structural frames to be beautiful; iron was “vulgar.” “Honesty” and “decency” seemed almost to be opposites. Even table and piano legs were deemed indecent and had to be decorously draped in cloth or sheathed modestly in wooden casing” (Peters 1996, 275). The material uncertainty and the attempt to define its strength with numbers as opposed to previous experience led to an advancement in engineering analysis methodologies (Rinke and Schwartz 2010a, 67).

Rinke and Schwartz point out that although the developments in iron “did not directly trigger the development of structural engineering and the process of separation in the disciplines, it was at least a catalyst. […] the novel, homogeneous and formable building material represented the promise of new foundational theories and precise processes of calculation: a comprehensive degree of control and a redefinition of the load-bearing structure. The increasing efforts to make the understanding of the load-bearing structure as well as the new building material more scientific had a radical influence on construction.” (Rinke and Schwartz 2010b, 19). Antoine Picon has also commented on its radical influence on how we design: “the advent of iron precipitated the abandonment of the Vitruvian tradition and the definitive split between the professions of architect and engineer.” (Picon 2010, 51). What this points to is that the innovation in material led to, or at least greatly accelerated, a change in how we design.

2.2 Concrete

Compared to steel, concrete maintains the monolithic and massive characteristics of stone. However, concrete had a more difficult time being accepted as an architectural material when compared to steel. Although it was developed in the mid-19th century, it was not until reinforcing steel technology developed and analysis of the hybrid material was perfected, that it began to be widely experimented with in architecture.

The development of concrete as a modern building material involved material innovation over the course of the 19th century in France by François Cointeraux, Jean-Auguste LeBrun and finally François Coignet, who worked through mixes, methods and aggregate types to develop the strength of the material. The material, however, was not widely accepted - reluctance in uptake was due to uncertainty about both its structural performance and its fire resistance. The structural history of concrete throughout the 1800s is riddled with failures. These were in large part due to inconsistencies in the quality of the material due to inconsistent workmanship and a lack of quality assurance processes. The result of this slowed down uptake led to the temporary end of the development in France for 20 years when Coignet went out of business in 1872 (Collins 1959, Chapter 1: Beton). The enthusiasm was then taken up in England and America for the next 20 years with the invention of formwork and an early form of reinforcing. However, a few failures also led to reluctance to use the material in these regions, enforced by the concern that the iron embedded in the concrete would rust. This concern did not disappear until well into the 20th century. Along with this resistance to use due to very practical reasons, however, was the appearance of the material. In 1870 concrete was honeycombed and motley in color. Victorians could not develop an affinity for the material and so the material was left to the engineers, who developed it further for large scale civil works (Collins 1959, Chapter 2: Concrete).

Iron reinforcing was the final innovation that propelled the use of concrete as we know it today. In 1873 in America, Thaddeus Hyatt was looking for a solution to fire proof iron, which had become known as more dangerous in a fire than heavy timber. The innovation he patented was the use of a steel beam embedded in concrete. He enlisted a retired railway engineer, Thomas Rickett, to help with the engineering calculations required. They developed the modern calculation approach to the bending in a reinforced concrete beam. They tested beams to failure both under load and under fire conditions and proved that steel and concrete expand at the same rate under heat. Furthermore, they proved that the concrete protects the steel, leading the way for use of reinforced concrete in hotels and many other structures. The results were published in 1877. By 1905, there were standard textbooks on structural reinforced concrete design. The standardization of both the material composition and the placement of the reinforcing finally led to structural reliability, material use efficiency, and its larger scale adoption, although full scale load testing was still required for most projects (Elliott 1992, 183–84). The ability to engineer thin shell structures in concrete advanced and by 1927, the Market Hall at Frankfurt am Main spanning 120 feet with 3-4-inch-thick concrete shells demonstrated this capacity. At this point in time, material efficiency was key, which made the use of vaulted structures desirable, especially in World War II when building materials were scarce.

The innovation in concrete was originally meant as a cheaper alternative to stone. The primary driver throughout its period of innovation was cost. Concrete did not develop as quickly as steel in North America due to its relatively higher cost in America than Europe. But once the material was recognized as reliable and fireproof as well as inexpensive, its broad-based use increased. Its social acceptance, similar to steel, lagged the material innovation.

3. Current Innovation Relating to Wood

As can be seen from the precedents of both concrete and steel, the innovation in a material application generally has a series of both technical and functional challenges that impact their wide scale adoption. These include change in societal expectations as well as developments in design, construction, engineering and analysis. However, these incremental developments in material and technologies can lead to more radical or systemic innovations. In some instances, a radical change may occur at the intersection of social and technical needs, as it the case with the Market Hall in Frankfurt, in others, it may open the door for a new design language in architecture. Wood is of particular interest in this discussion as it is not newly invented, but instead, it is one of the oldest building materials. At the current intersection of much larger cultural and social challenges, the sustainable aspects as well as innovations relating to the sourcing, processing, and use of the material have renewed the interest of consumers and municipalities, as well as architects and engineers. Due to the long history of traditional wood construction it may be necessary to challenge pre-conceived notions; a change in the language of wood architecture is arguably more difficult than the invention of a new language for a new building material. That said, its accessibility as a resource combined with the economy of scale makes wood a very valuable focus for continous innovation. It is therefore worth examining in more detail what innovations in wood might be and how to take advantage of the material within the framework of a new technology. Through this lens, the presented projects begin to ask the question of what the future of building in wood may look like.

3.1 Innovation – customized timber products

Sustainability concerns have brought a renewed interest in timber construction and with it, the development of new timber products. Plywood, Laminated Veneer Lumber, Glulam, and CLT have been developed to increase homogeneity and create dimensional stability in otherwise anisotropic materials. Each product and each subcategory of it, while exhibiting general enough characteristics to be used in very different types of buildings, are made, and subsequently optimized, for a particular structural purpose. Each has its grain oriented for a specific structural behavior or a specific loading condition. In addition, many of these industrialized standardization processes have been instrumental in positioning timber products as a prime material for design and construction. While expanding the range of mass applications for timber products is an essential dimension of industrial and academic research, developing new value-added products and high-performance applications requires a more inquisitive approach. Recent work into structural variability of timber components (Self, 2017), integrated Joinery (Robeller, 2017; Krieg, 2013), custom-laminated doubly-curved components (Meyboom 2015), or environmentally active shape-changing wood systems (Reichert et al, 2015) and actuators (Ruggeberg, 2015) present a new conceptual approach that is decidedly specific to the performance characteristics of wood. These advances have only been possible through a multidisciplinary approach to material research and the development of specialized computational design-to-fabrication tools.

Moreover, a growing number of innovative architecture projects have started to build on this material specificity in wood. For instance, the precise manipulation of grain orientation for a specific architectural intent has been implemented in Shigeru Ban's curved elements for the Haesley Nine Bridges Golf Course Club House. The structure is made from custom laminated veneers, manufactured by Blumer Lehman, that have been structurally designed for specific architectural applications rather than a generic structural loading condition. The ability to customize wood's performance, through material engineering and fabrication, for its structural requirements is one of the reasons for its large potential in the 21st century.

3.2 Innovation – digital design

Today's planning processes in building construction are well on their way to becoming digitalized, but they are also fragmented into different disciplines (Kieranamp and Timberlake, 2004). On the one hand, digital planning processes may allow for more complex and potentially performative buildings. On the other hand, they are currently still characterized by a top-down design development where questions of producibility and materiality are only answered at a late stage of the design process. The current situation causes not only higher planning costs through changes in the design, but it also requires more time and effort for manufacturers.

Leaving material performance and fabrication parameters for later stages perpetuates the disconnect in the design practice between form generation and materialization. This modus operandi leaves architects to design forms with limited fabrication understanding while it simultaneously leaves builders and fabricators in the precarious and costly position of fabricating structures without an understanding of the intended architectural design performance. A common example of this disconnect is the use of complex steel frames made of linear elements to build a framework for a building skin, or covering, which manages to simulate the fluidity of the form in the digital design such as the Burnham Pavilion in Chicago and the Riverside Museum in Glasgow by Zaha Hadid Architects. This however, is inefficient and illogical when compared to the ability to simulate the natural bending capacity of the material itself to represent the flow.

3.3 Innovation – engineering analysis

There is a general ambition that architectural design software may one day be able to accurately simulate material acting structurally within its elastic range, and one could imagine that this type of innovation, when available, would assist architects in their pursuit to work with wood in innovative forms. However, at this point engineering software still has difficulties with the biological and anisotropic characteristics of wood in plain members. It is still relatively difficult within mainstream engineering analysis software today to simulate wood with different strengths in different directions due to grain orientations. Moreover, engineered wood can either make the problem better or even worse: if the wood is layered in ways that create a more isotropic material, this simplifies the material characteristics but, in some cases, multiple layers of laminate require the layering of already anisotropic layers of the wood, creating an even more computationally complex material. These current limitations render the implementation and testing of these models extremely labour intensive, or their complexity makes them so computationally expensive that it becomes impractical to compute for most building construction applications.

In order to analyze many of the projects mentioned in the previous chapter, a custom written staged finite element analysis is required that looks at each stage of loading and how much of the elastic limit of the wood has been used prior to live loading (Lienhard 2011). This type of software is more common in mechanical engineering to simulate staged loading but such a simulation is difficult to set up and complete, especially with a material with varying grain structure and joints whose behaviour are not conventionally known. In the experiments presented here, the scale of the structures was small and estimates regarding behaviour were carried out so that the benefits of the demonstration could be seen, with the knowledge that much more analysis and sophistication in the engineering software is required before deployment on a non-experimental application can take place.

3.4 Engaging with Material Characteristics

In addition to bending stiffness and its inherent anisotropic behavior, it is equally important to note that wood's material behavior and unique fibrous characteristics come from its primary function as a naturally grown biological tissue.

The difference in cellular orientation across different species is critical to the appearance and the structural characteristics in the transverse or radial plane of wood. More generally, in the case of both softwood and hardwood species, the structure, distribution and orientation of cells are the determining factors in the anisotropic structural and hygroscopic characteristics of wood (Wagenführ 1999). Accessing wood’s material complexity in a meaningful way requires a re-conceptualization of architectural design that moves away from a single focus of form definition and building performance, to a more bottom up approach of design formation. In the latter, material behavior is an intrinsic component of building performance, from embodied energy (Alcorn 1996), indoor moisture mediation (Simonson 2001), fire resistance, structural performance, to form generation.

The inter-dependence between materials and building performance is not new in and of itself, but the quantitative understanding, albeit primitive, of their behavior is. To develop predictive models for both building performance and the fabrication of building components, a wider range of computational tools needs to be engaged, where management of information becomes critical. Whether it is the acquisition and catalog of data, simulation of structural behavior, simulation and control of fabrication processes or the translation of data across several unrelated computational platforms, each step requires its own set of information modeling tools. It is important to note that many of these tools and methods are new while many of them have been borrowed from initially disconnected research fields such as material science, engineering and manufacturing. Therefore, the communication and translation of different performance goals, data types and design criteria across multiple disciplines are essential in the success of this research.

Elasticity

The uses of elastic bending for form finding in building construction is relatively infrequent, as architects and engineers alike are generally trained to understand larger deformations as potentially dangerous. Active bending for instance, describes curved beams or surfaces whose geometry is defined by the elastic deformation of initially straight elements (Gengnagel 2012) (Lienhard et al. 2011). Active bending has been employed in prototypical timber structures in the last years (Menges 2011a, Krieg 2013, Bechert 2016) resulting in an innovative approach to the material whose form embodies both the forces and the structural material characteristics of timber itself. In bending active structures residual stress caused by elastic deformation is used to act against external forces, such as load bearing, by increasing their geometrical stiffness. Although integrating this material behavior poses a challenge due to the complex interrelation of force, form, and fabrication, it can provide unique formal and structural design opportunities that can facilitate a much more effective use of the available material and thus fosters a material-based architecture. One of the most advanced examples of elastically bent wooden structures is the lattice shell of the Multihalle in Mannheim by Frei Otto, Carlfried Mutschler and Ove Arup & Partners, completed in 1975 (Burkhardt 1978). Wooden lattice shells are structures, which are initially constructed as a planar lattice of timber laths and are later hoisted or lowered to form double-curved, form-active surface structures. Here, the design approach has to incorporate both the flat, two-dimensional state, and the elastically bent, three-dimensional state of the grid shell. Taking the material's elasticity into account it was possible to fabricate the double-curved grid shell from straight, planar, solid timber elements. The work outlined by the projects presented by the authors continues this investigation – looking at customizing material and its application to work together to create expressive and material informed structural forms.

Hygroscopicity

Unlike other construction materials developed to meet specific manmade functional requirements, wood has evolved as a highly efficient biological system to meet the support, conduction and storage requirements of trees. All of its differentiated material properties are themselves intrinsic to its physiological role within the tree as a living organism and as such, they exhibit a great range of variation (Dinwoodie 2000). Furthermore, within every geographic region, trees evolved into locally adapted species and sub-species with differentiated material behavior in response to atmospheric conditions, soil, seasonal changes and fauna. In other words, a bespoke material for every ecosystem.

Considering this local adaptation can help in developing architectural and building solutions that are more resistant to specific climatic conditions, it can foster sustainable sourcing of materials or support the re-conceptualization of existing wood construction technologies in new contexts. However, it is also possible to augment some of these biological characteristics to create new high-performance building systems and components. One of the key biological characteristics of wood, as a vascular tissue, is its dimensional change in relation to atmospheric conditions. The complex cellular, polymeric composite characteristics of wood and its structural performance implications are closely tied to the role of cellulose within the cell walls. The cellular, axial differentiation of cellulose molecules within the fibrils and micro-fibrils defines many of its structural properties, and it also establishes wood's characteristic hygroscopic behavior. This anisotropic expansion generates high pressures that can greatly vary from specie to specie, from high theoretical values of up to 165 MPa (Stamm 1964) to a more conservative 83 MPa (Turner 1958), depending on the testing procedure, as explained by Rowell (1995). Extensive research on limiting or controlling these dimensional changes has been conducted by the timber industry, but very limited work has been done in integrating these expansion forces within design applications. The presented work builds on the limited studies on wood movement and joinery by Eckelman (1998) as well as the more recent development of shape change bilayer wood actuators by Reichert et al. (2015), Holstov et al. (2015) and Rüggeberg (2015); as well as the work on 3D printed hygroscopic wood actuators by Correa et al (2015). Both wood joinery and actuators engage the dimensional expansion of the material as a key performance characteristic, and therefore, as a key driver of the design. Considerations of shape, fabrication and assembly are carefully considered in relation to the relative humidity (R.H) of the environment as well as the equilibrium moisture content (EMC) of the material itself. This integration seeks to precisely use and augment the hygroscopic expansion properties of the material to employ its effects, for assembly or shape change, without external electronic mechanic sensors, controllers or actuators. The authors are building on this research by using the intricate responsiveness of the material to aid in the assembly and inter-locking fastening of timber elements in a larger building system.

3.5 Innovation – fabrication

Digital fabrication tools like CNC machines have become well established in wood fabrication in the last decades. Their main advantage lies in automating individual aspects of the production and thus making standardized processes faster and more efficient while at the same time exceeding the quality standards of manual fabrication. However, due to their complexity in programming and operating, most wood processing machines have been equipped with closed, “black box” systems, with user interfaces designed to simplify these processes by incorporating pre-defined mass production fabrication workflows. This approach has been very successful in making the technology accessible and therefore ubiquitous on every shop floor. However, advanced users find themselves at odds with the overly constrained methods and the limitations of a “black box” approach.

The industrial robot constitutes an opposite approach to these highly specialized systems in both practicality and applicability. The multi-axis robot arm represents a generic platform on which a multitude of tools, so-called effectors, and generic Numeric Control platforms can be attached. Control platforms and effectors are developed by multiple vendors, researchers or academic institutions, unrelated to the robot manufacturer, but according to the tool or application. These NC tools range from open ended multi-purpose applications to “black box” niche uses. It is therefore only the effectors and the NC platform, or a combination of those, that will ultimately define the variability and potential of the fabrication process. The potential of industrial robots in wood construction ultimately derives from their extended kinematic range and their adaptability to new fabrication processes, through custom effectors and varied NC platforms, making the fabrication of more complex and differentiated building parts possible. Most important yet, the ease in adaptability of the industrial robot facilitates a shift in IP generation that does not rely solely on the product but on the development of adaptable fabrication platforms. Nevertheless, to really take advantage of the hardware’s flexibility the main challenge lies in the development of a robust and open design-to-fabrication computational workflow with a direct digital transfer of machine data from design to manufacturing.

One of the main foci of this research is therefore the demonstration of the implication of digital fabrication technology on how wood could be conceived and applied. The 7-axis robot setup used in these experiments allows a very large range of options for shape definition and assembly of wood components. This freedom combined with the accuracy of the tool allow for tight fit joints at very precise angles. This new-found fabrication ability in wood has been used here in three ways: to create a very precise joint capable of transmitting structural forces in predicable ways; to create informed free-form geometries, which are precise and allow subtle changes in curvature in response to natural material bending curvature; and to allow fabrication and assembly instructions to be embedded within the component elements of the installations themselves.

3.6 Innovation: Summary

The projects shown in the following chapters attempt to engage with innovation in wood in the areas discussed above. We can see why innovation is halted across disciplinary borders and this research seeks to demonstrate an integrated approach that facilitates innovation. Digital design does facilitate interdisciplinary collaboration. However, when looking at such a radical change as the industrial robot in combination with the evolving digital technologies, the entire conventional working methodology has the potential to be disrupted. For example, the integration of accurate engineering analysis and machine control into architectural software could produce unforeseen disruption. In addition, the highly precise tolerances of the robot and the ability to easily fabricate any shape or joint condition allows innovation. Further, more innovation can be expected from the advanced understanding of material characteristics, which can be integrated and taken advantage of in the design process, rather than homogenized, approximated or ignored. All of these aspects can be combined into a radical innovation in how we use and think about design in wood.

4. Methodology

The presented projects focus on the design and fabrication of two large scale, robotically fabricated, timber prototypes developed at the University of British Columbia, Center for Advanced Wood Processing, in collaboration with the Institute of Computational Design and Construction at the University of Stuttgart, and the School of Architecture at the University of Waterloo, through two separate interdisciplinary workshops. The workshops were led by the authors (architects and structural engineers) in close collaboration with local wood researchers, industry participants, international faculty and students. Each prototype integrates a different set of material performance goals but also different methodological strategies for both design intent and assembly. Technically, the prototypes were developed using integrated ‘design-to-fabrication’ computational and form finding tools, implemented using a 7-axis robotic milling set-up.

Until now, traditional design processes in wood are typically clearly differentiating between linear and planar elements in a hierarchical manner. In the case of the innovations discussed here, the material takes on a design flexibility and a facility with form. This form, however, is not imposed on the material but rather informed by the material. The material characteristics, limitations and structural properties inform the design, providing constraints but offering possibilities. The resulting techniques and forms are presented here as initial steps towards a new language of design in wood, which will better reflect the current design ethos.

Both material characteristics and fabrication possibilities were investigated in parallel for the development of new construction systems. The presented prototypes reveal both structural and architectural performance characteristics that are unique to the presented integrative design approach. Their contribution here lies on the reciprocities between prototyping robotic fabrication and material-based computational design. Both prototypes explore the concept of inherent assembly instructions. Most of the building elements can be assembled without external instructions or plan drawings because their assembly information is already inscribed in the connection geometry. This method also ensures that the building elements are elastically bent into their correct shape.

5. Results

The experimental installations created were full scale applications of the developed technologies. Both were created with a custom design to fabrication computational tool allowing for the direct generation of machine code from the design files. Both prototypes were designed and built during workshops held at the University of British Columbia.

5.1 Prototype 1

The first prototype explored elastic bending of large scale timber sheets for double-layered timber structures through a combined approach of material-oriented design, traditional wood joints, and robotic fabrication techniques (Fig. 2-9 & Fig. 21). Working with the hygroscopic and elastic capacities of wood, the project uses elastically bent plywood sheets to form a finger jointed, segmented, double-layered shell. Each joint is designed for self-aligning and self-locking through the hygroscopic expansion of integrated dowels, as described in section 3.4. The geometry, joints and bending radius are parametrically defined within the custom design-to-fabrication computation model. The direct associations, boundaries and other design constrains are visually represented in the model. This visual access within a design platform allows participants to develop multiple formal iterations while mediating design intent with material and fabrication constraints (Fig. 4). The tool enables participants, with different technical backgrounds and expertise, to provide design input at multiple hierarchical levels, from global shell articulation through a double-curved surface to precise multi axis control of the tooling path for the integrated 7 axis robot milling set up.

Figure 2 (left): Photograph of the finished prototype made from a finger-jointed, double-layered, elastically bent plywood construction.

Figure 3 (right): Detailed photograph of the structure under construction. In the front, the extended finger joints and shear dowels are visible.

While the elastic bending of timber sheets has been thoroughly explored by multiple research institutions in the past years, their application in large scale construction is prohibited by the relation between maximum bending radius, bending forces, and material thickness. Generally speaking, timber construction elements usually have a material thickness not suitable for elastic bending as a visible bending radius would not be achievable during assembly. Instead, a multi-layered approach was investigated in the first prototype, combining two layers of plywood sheets thin enough to be bent manually, with two people on site, but resulting in enough material cross section in aggregation to potentially carry higher loads in a larger structure. For this purpose, both layers are interconnected with wooden shear dowels and spacers (Fig. 3, Fig 5 & Fig. 6). This method allows for an additional space between the layers, allowing them to act as a hollow sandwich panel. At the same time, the dowels are placed in such a fashion that the two plywood layers can only be assembled when elastically bent into their final shape.

The double-layered configuration allowed additional structural opportunities, however, it also necessitated further development of curved finger joints for plywood plates, building on previous research by the authors (Krieg 2013). For this purpose, the finger joint was further developed to facilitate the assembly sequence while maintain its structural capacity. Both plywood layers are connected to their neighbors in consecutive fashion, allowing for finger joints to reach through both layers of the neighboring elements. This type of multi-layered intersecting finger joint allows to rely only on wooden dowels to lock the connection after assembly (Fig. 5 - 6). The necessary geometric information to generate the milling tool path can be computed by the geometric relationship of two or more connected plates in their final bent geometry, and their equivalent flattened, or unrolled shape. As the connection angle and bending radius changes along the connection seam, the tool path and vector are generated for each single joint and slot individually. Their parameters are informed by their position on the bent geometry and transferred to the flat plate. Through the developed fabrication method, it is possible to cut curved finger joint seams that specify the plywood sheet's bending radius and geometry through the individual joint's shape and position. The resulting joints along the curved seam only fit into their adjacent plate's joints when the plywood sheet is elastically bent into its correct shape (Fig. 4-7).

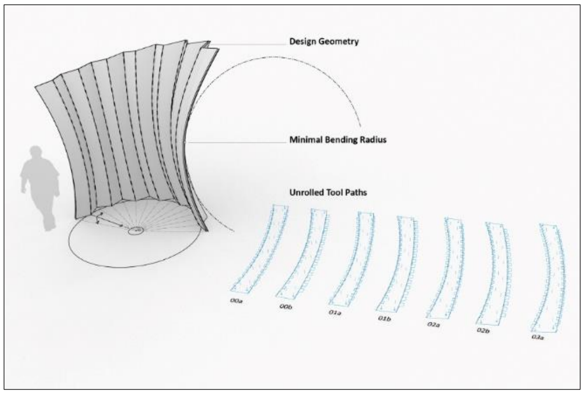


Figure 4 (left): Visualization of the computational process from the design model to the fabrication data. The individual plywood strips get unrolled before the joint geometry and milling tool paths get applied.

Figure 5 (right): Visualization of the double-layer construction, the finger joints, and the wooden dowels that lock the connection in place.

While the modulus of elasticity of the plywood sheets is used to define the global form, the final assembly geometry is locked in place through the hygroscopic expansion of the wooden dowels. Based on traditional wood joinery methods, as per section 3.4, the hygroscopic characteristics of the material are used to ensure a rigid and permanent connection. In contrast to the plywood sheets that do not react to changes in relative humidity due to their cross-laminated veneers, the wooden dowels consist of solid hardwood and therefore change dimensions depending on their relative humidity. To allow for precise assembly, the diameter and moisture content of the dowels is checked and equalized prior to fabrication – all dowels' nominal dimension and moisture content must be consistent. The dowels' moisture is then reduced to 4-6% EMC, or "dried" state, in a climate-controlled chamber resulting in a 5-10% change in diameter. The perforations in the plywood sheets were milled according to this smaller diameter, and therefore allowed the dowels to be inserted in their "dried" state, and to become "locked" in place after adjusting to the surrounding atmospheric humidity (Fig. 6). The coupling of elastic bending and hygroscopic expansion allows for the complete assembly of the self-standing structure without the need for any metal fasteners or molds (Fig. 7).

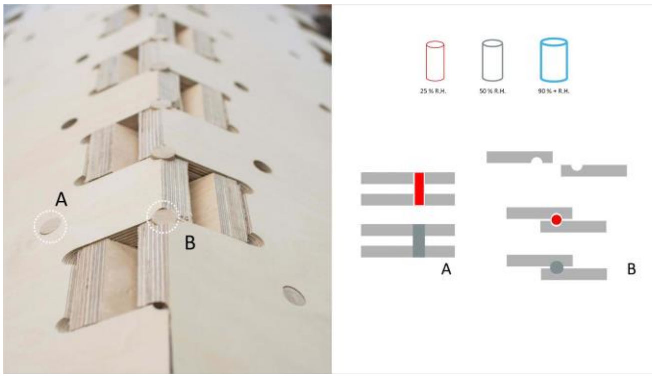


Figure 6 (left): Detail photogram and diagram for the hygroscopic induced locking mechanism of the panel using wood dowels.

Figure 7 (right): Photograph of the finished prototype for the double layer structure.

The initial design of the prototype was conceived by understanding the relationship between the locally elastically bent plywood strips and the connection angle to their neighbors. In order to create a sufficiently expressive curvature, a thin plywood was selected and the strategy of folding back and forth at the connections was engaged to provide an additional structural depth to the shell form in order to increase its structural stiffness while still maintaining the fluidity of the curved form, which requires the elasticity of the material for its expression. This provided the additional benefit of controlling the sheet size and maintaining a single curvature in the plywood sheet elements.

Figure 8 (left): Robotic fabrication of the individual sheets. The fabrication data was directly exported from the computational design model.

Figure 9 (right): Back side of the final prototype assembled on campus.

5.2 Prototype 2

For the development of a second construction system and subsequent prototype (Fig. 1 & Fig. 10-19), the authors investigated the relationship between assembly instructions and the geometric specificity of building parts for the construction of a doubly-curved building system. By encoding the assembly instructions for a set of generic stock components into a different set of specialized, CNC milled, building parts, traditional instructions such as plan drawings become redundant. In addition, this strategy allows to fabricate and construct elaborate timber structures partly from off-the-shelf building materials. By combining two approaches – highly specific and prefabricated building components, and standardized “stock” materials, the authors investigate the technical and architectural reciprocities between mass production and bespoke fabrication. More specifically, by coupling stock cedar planks with a robotically fabricated diagrid substructure, the project uses geodesic methods to create a double-curved “timber wave” (Fig. 10 & Fig. 14 - 15). The diagrid substructure can be assembled on site and is flexible but self-supporting at first (Fig. 12). The intersection points of the diagrid are designed to be structurally rigid only in combination with the horizontally arranged cedar planks. These cedar planks are initially straight, and normally used as standard horizonal cladding (Fig. 11). In this project, their functionality gets extended by fixing them directly on the diagrid’s intersection points (Fig. 13). The diagrid is made from two layers of CNC milled plywood strips, which, although initially planar, are not straight but curved; the cedar planks, on the other hand, are initially planar and straight. Both the diagrid and the cedar planks are elastically bent to achieve the final structural assembly (Fig. 16). This additional constraint limits the design space of double curved surfaces as the planks can only follow so-called geodesic lines. Therefore, the planks become the defining design criteria.

Figure 10 (left): Photograph of the finished prototype. The front face prominently shows the bent cedar planks following the double-curved surface.

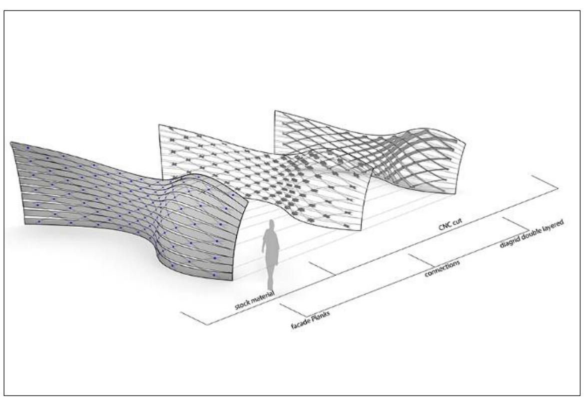
Figure 11 (right): Detailed photograph of the diagrid substructure. The diagrid is double-layered and has thick plywood spacers at the intersection points, which also act as connectors to the cedar planks.

In this project, hygroscopically activated wooden dowels are used to self-align and fasten the diagrid components making metal fasteners mostly redundant. In this case, the diagrid is double-layered but connects to thick plywood spacers at its intersection points. In order to ensure a permanent connection between these elements, dried wooden dowels are inserted during assembly. As the installation is located on site, exposed to a higher R.H. environment, the dowels equalize their moisture content and therefore expand to lock the layered connection.

Figure 12 (left): Detailed photograph of the diagrid substructure during assembly.

Figure 13 (right): Detailed photograph of the cedar plank during assembly. Intersection point of diagrid is half exposed awaiting fastening of the next plank.

Similar to the first project, the ‘design-to-fabrication’ approach and computational tool enables the designer to engage with a complex technical problem through a visual and design-oriented methodology. At the higher level, a double-curved surface model provides global feedback on curvature and overall shape while subsequent steps allow for parameter manipulation of plank overlap and joinery. Also, in this project, the computational design tool pre-visualizes the result of the elastically bent building elements but also recalculates their initially planar shape for fabrication. This becomes especially evident when the design tool calculates the unrolled state of the cedar planks, proving that they are initially straight and planar. A simulation of the robotic milling process and export of robot control files are fully integrated in the computational design process. Divided into two complimentary systems, the diagrid provides precise geometric definition through robotic fabrication and self-aligning hygroscopic joinery, the planks are then easily aligned with the diagrid and fastened through standard wood screws.



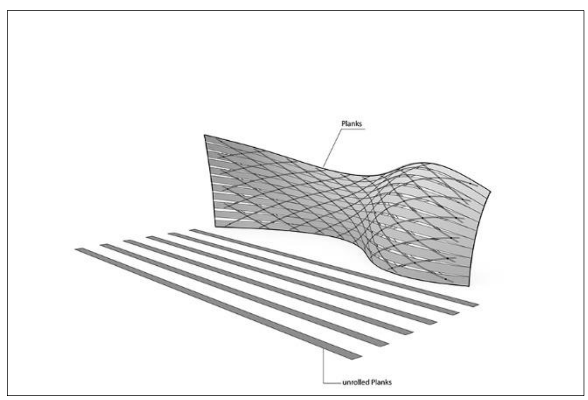


Figure 14 (left): Visualization of the diagrid elements and multi-layered assembly system. The double-curved design surface is constructed with a double-layered diagrid and thicker spacers at its intersection points.

Figure 15 (right): When unrolled from the design model, it becomes evident that the cedar planks are indeed straight. They are only bent in one direction when connected to the diagrid.

By using advanced timber fabrication techniques and taking full advantage of the extended fabrication range of the multi-axis set up, large sections of plywood were custom milled and assembled on-site into a unique one-to-one scale architectural prototype. Once assembled, the diagrid and the cedar planks form a stable, doubly-curved building system. The prototype showcases distinctive wood fabrication possibilities that integrate computational design, material characteristics, and digital fabrication in a direct design to production paradigm, leading not only to innovation in timber construction, but also for a re-interpretation of wood architecture.

Figure 16 (left): The diagrid structure and the cedar planks during assembly.

Figure 17 (right): From the back, the relation between planks and diagrid can be seen.

6. Discussion

Completed in week long workshops, the prototypes offer evidence that the unique anisotropic and hygroscopic properties of wood have many unexplored design opportunities. The contribution of the prototypes presented here is their ability to position wood as a driver of design intent and form. A contribution that is only possible through a careful material understanding as well as a robust design to fabrication workflow capable of integrating complex parameters and associative relations inherent to fabrication, assembly and material performance.

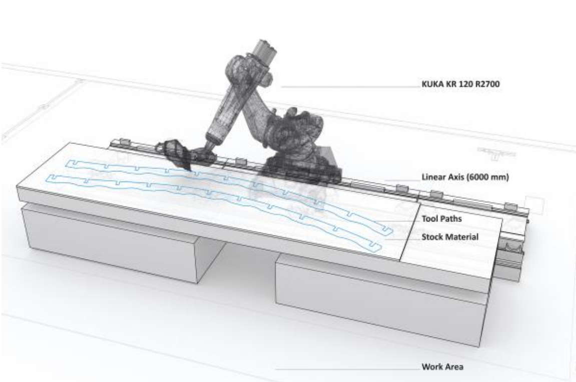


Figure 18 (left): Diagram of fabrication components on the 7 axis robotic system.

Figure 19 (right): From the back detailed photograph of the diagrid substructure.

The projects are case studies for both a manifestation of a design paradigm as well as an assertion about the potential of integrated research into the potentials of wood, and a re-emergence of applied research teaching methodologies. Using Picon's words (2010), "innovation comes about at the intersection of technical and social issues that need to be decoded". In here, the innovation is foregrounded primarily to be one of material informed design, but in this discussion, it may be worth considering another contingent dimension of the work. In an era of unprecedented connectivity and global economies, disciplinary research remains a highly territorialized domain. The development and execution of these projects as week-long workshops as opposed to term long academic endeavors, is indicative of the larger challenges that lie ahead. While interdisciplinary research is highly lauded as a pinnacle of modern research, institutional structures of disciplinary funding and professional teaching accreditation struggle to identify frameworks that can support these types of initiatives. As presented in chapter 2, 2.1 and 2.2, technical developments or architectural design visions in isolation are not enough to support meaningful building construction innovation. Disciplinary fields can address individual challenges of quality control, structural performance, system integration or visual expression. Meaningful development of new technologies into commercial applications, however, only emerge at this intersection. Interdisciplinary research at full scale, like the work presented here, is positioned to be fertile ground for this type of exchange. The learning opportunities offered by full scale prototyping projects are unique as they provide a defined scenario with real testing conditions for design investigation, quality control, structural performance testing, material research, project management and cost evaluation (Fig. 20-21). An integrative design process, or design to fabrication process, is by definition and inter-disciplinary design process. Computational, robotic, structural, material and pedagogical tools and methods are positioned in support of each other both within and outside of disciplinary boundaries.

Figure 20 (left): Hands-on robot control training during Robotic Fabrication workshop.

Figure 21 (right): Manual assembly of elastically bent double shell prototype structure during Robotic Fabrication workshop.

7. Conclusion

Each prototype begins to demonstrate the potential of wood beyond current practices. While mass industrialization capitalized on large-scale use of stock components, demonstrated by stick frame construction, mass customization has focused on the imposition of homogeneity on the varied anisotropic nature of the original material, as can be seen with CLT, MDF, plywood, OSB and other CNC optimized materials. Both technical and material innovations are not in themselves sufficient drivers of meaningful change in architectural language or building practice. It is important to remember that it was not only the development of reinforced concrete or steel that brought about its implementation; meaningful innovation emerges at the intersection of needs and opportunities. The development of steel necessitated a new design language and new specialized disciplines to truly have an impact in the built environment, while concrete required the development of methodologies for construction standardization and disciplinary expertise before becoming an architectural staple.

It should be said that while technology may provide some answers to the practical aspects of implementing materials in architecture, it cannot provide a road map for research and on its own is unable to foster design interest or aesthetic performance. The prototypes presented here do attempt to demonstrate the importance of a conceptual shift from representation and form definition to informed material investigation, the re-purposing of robotic fabrication as method for informed material manipulation and the role of teaching as shift from lecture to active interdisciplinary dialogue. These investigations take small steps toward the larger research agenda of looking at what might be possible in wood in the future, what are the architectural languages and building types that these new possibilities can facilitate.

The projects are presented as a medium to begin a dialogue about methods of construction: integration of material behavior in the design process, integration of computational tools and fabrication processes and most importantly, the knowledge transfer to new architects and designers. The development, execution and teaching methodologies necessary for these projects have inevitably generated larger questions about disciplinary roles, existing design paradigms and the potential of future powerful design, analysis and fabrication tools - questions that are essential for the future of the practice and the sustainable future of our cities.

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