INTEGRATED DIGITAL DESIGN AND FABRICATION STRATEGIES FOR COMPLEX STRUCTURES: RE-EXPERIENCING WOOD JOINERY IN ARCHITECTURE

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ABSTRACT

Throughout the history of architecture, the developments in material technologies and related fabrication techniques have played important roles in the design and construction process of a building. Human being has attempted to create spaces to meet sheltering needs and while creating spaces he has used and formed materials around him. Wood was one of the appropriate materials that was not only economic and aesthetic, but also strong in tension, compression and bending, allowing triangulated space-frames or trusses and cantilevered structures, etc. In this context, this research attempts to understand the relationship between complex wooden structures in architecture and digital fabrication of wood joinery. By studying and analyzing selected case studies, the article will address the following questions: What are the changes that have occurred in architectural design and fabrication of wood joinery due to the use of computational design and digital fabrication technologies? How can wood serve architects in “materializing the complexity” of this era? Furthermore, the importance of re-searching new tectonics and materialization technologies while re-thinking of wood as a “new material” in architecture is discussed through the selected examples.

Keywords: Computational Design and Fabrication, Wooden architecture, Wood joinery.

1. Complex Forms and Structures of 21st Century Architecture and the Potentials of Wood

The use of CAAD in architecture has been extended from being a medium of representation to media of design and manufacturing CAD/CAM, CAAD has also served a shift from exclusively designing the product to inclusively designing the process. There is no doubt that CAD/CAM applications have been rapidly changing the conventional architectural design and construction processes since the end of the last century. In this process, researchers and practitioners have been seeking for new tectonics and materials which reveal the beauty of using cutting edge technologies without sacrificing the “sustainable” aspect of the manufacturing process. Advances in material science, interdisciplinary studies and innovative design and fabrication technologies as well as extremely high data crunching capacities have resulted in changing the perspective regarding the role of materials and consequentially "Digital Materiality" emerged as a new sustainable architectural process that explores the materials' physical potentials (Booth 2009).

The complexity of the building design problem resulted in complex design output that crossed the boundaries of Euclidean geometries to more freeform topological geometries which now computational design approaches attempt to design and manufacture. When the use of computational design approaches and enabling technologies in architecture in the beginning of the 21st century is considered, it is seen that design and fabrication are becoming an integrated process in which the constructability of a design proposal is being simulated, evaluated and tested in early design stages. Several tools for digitally fabricating materials, including wood, have been developed in parallel to the development of CAD/CAM and CAAD such as laser cutters, CNC and robotic production that allowed new methodologies for complex structure design and fabrication.

Wood has been used as a main building material for centuries. Wood craftsmanship over time has developed tools and geographically and culturally customized building systems. Tools have developed from hand based to machine based, and from machine based to information based. O’Brien (2000) states that building system started with a simple log structure that used large refined pieces of wood from trees as well as skeleton timber frame structure with smaller pieces in other geographical locations. Later on and prior to the industrial revolution, wood started to be processed in small standard sized pieces that were assembled to produce light wood frame structures. Then in the information age, CAD/CAM technologies eliminated fabrication constrains, and are now gradually unifying the practice worldwide.

It should be mentioned that the advantages of wood as a strong, durable and renewable material in the realm of sustainable design, its availability, ease of construction and high performance, increase the interest in wood as an important alternative for CAM and fabrication. In fact, realizing the potentials of wood through the use of CAAD and fabrication technologies is one of the aspects that drives the renewed interest in using wood as a structural building material (Bocanegra et al. 2014), in digital manufacturing; wood has many advantages that bring appropriate fabrication possibilities and testing for parametric conditions, easily cut and repaired, wide varieties for connection types and offering divers range of geometric explorations (Beorkrem 2013, p. 14).

Table 1 contains examples of innovative application of traditional wood building systems in a selected buildings and pavilions, the table highlights the following: (1) The innovative application of traditional wood building and fabrication systems that inspired, with the help of computational design and digital fabrication strategies, the achievement of complex freeform structures, see examples number one, three, four, and five (2) The development of a building system for multi-storey wood structures, see example number two (3) Common technique that is used in other domains such as furniture design, kerfing, that is rephrased in parametric conditions for two wood pavilions, see examples five and six.

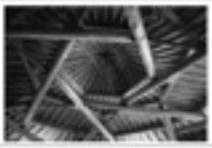
INSPIRATION	ANALOGUE TRANSFORMATION
	
1. Log Structure A traditional timber building system where horizontal logs stacked one upon the other providing the cladding, enclosing and loadbearing functions.	The Biomass Boiler House, 2015: For constructing the outer double curved wall from wood in its natural form 3D scanning was used to compile a data base of selected 250 curved trees. the optimum position of each curved trunk was determined using scripting routines and pieces were matched accordingly to the structure's 3D model.
	
2. Timber Frame Structure A load bearing framework of large structural timbers primarily connected with wood joinery such as mortise and tenon, oblique and halving joints. Structure In figure: Jodo-ji Complex,Japan.	Tamedia New Office Building, 2013: Seven storey timber frame structure constructed with using wood joinery.
	 
3. Pre-stressed Timber Gridshells Constructed from lattice with a fixed topology, which is first laid out flat and then pushed up from certain points to obtain the double curved form. Structure In figure: the Mannheim Multihalle, 1975	(left) Smart geometry Pavilion, 2012: A wooden gridshell assembled from straight wood members bent along geodesic lines on a relaxed freeform surface. (right) Ongreening Pavilion, 2014: Utilizing wood's elastic behaviour; the structural approach involved form-finding and bending-active plywood laths, geodesic lines originated from selected points on the surface were unrolled to form straight lines leading to an efficient 3-axis CNC fabrication.
	 
4. Zollinger Lamella Structure Type of lamella roof construction which consists of crisscrossing pattern of parallel arches of relatively short members hinged together and form an interlocking network in a diamond pattern.	Lamella Flock Pavilion, 2010: A freeform structure of straight beams following the principles of Zollinger lamella construction. The non-standard production was achieved through the use of heavy production techniques using glue lam, complex joints, and 5-axis milling.
	 
5. Reciprocal Frame Structure A structure made up of mutually supporting beams in a closed circuit.	Dragon Sking pavilion, 2012 (Left) and IBOIS modular timber structure prototype, 2012 (right) are both examples of planer morphology of reciprocal frame structures
	 
6. Wood Kerfing Wood bending and twisting technique using series of cuts to direct bending and wrapping.	(left) Performative Wood Studio- Kerf-Based Complex Wood Systems, 2010 (right) Kerf pavilion , MIT Department of Architecture, 2012.

Table 1: Innovative Application of Traditional Wood Building Systems (Sahu and Wang 2015; Tynkkynen 2012; Tamke et al. 2010; Menges 2010; Menges 2014; MIT Architecture 2012; Laboratory for Timber Construction

IBOIS 2012; Harding et al. 2015; Ramboll Computational Design 2014; Larsen 2008; Cabrinha 2012; MATSYS Design 2012; Kolb et al. 2008, pp. 51,52,54,55; Shigeru Ban Architects 2013; Zwerger 2012, pp. 93,147)

2. Wood Joinery

In wood structures connections can be classified into two major types, chemically (glued joints) using adhesive, or mechanically by using either dowelled joints or traditional joints referred to as wood-to-wood joints, carpentry connections or wood joinery. Wood Joinery is the oldest among other types of connections (Jeska et al. 2014, p. 59), Messler (2011, p. 316) identified Wood Joinery as "the mating of two or more surfaces [in wood components] to form a solid unit that serves a specific function", the specific function of structural wood joint as addressed by Mönck (1985, p. 77, as cited in Zwerger, 2012, p. 100) is to " join together pieces of timber permanently and securely in such a way that the required structural interaction of the constructional element or the construction itself is enabled". Wood joinery developed through hundreds of years of carpentry experience, from log structures with one type of joinery connecting logs edge-to-edge to a more complex timber frame structures with multitude of joinery types for various functions.

In the 19th century wood joinery experienced a major shift because of the industrial revolution; steam driven machines and mass production changed wood structures from timber frame structures of varied components with manually produced wood joinery that is labor intensive into balloon frame buildings of economically mass produced standardized components and metal connections (Jeska et al. 2014, p. 59). Manufacturers of metal fasteners provided extensive analyses and comprehensive tables of load-bearing capacity calculations. Such tables never existed for wood joinery and as a result metal fasteners became easier and more manageable for assembling wood structures (Messler 2011, p. 318).

According to Jeska et al. (2014, p. 60) By the middle of the 1980s, with the introduction of CNC technology, an integrated workflow from design to fabrication along with designing and manufacturing process of joinery parts with high precision and speed became possible. CNC milling and later the five-axis CNC and six-axis with robotic arms milling machines allowed for mass customized fabrication of wood joinery without incurring extra costs. Similarly, Tamke and Thomsen (2009) states that by that time the efficient production of geometrical complex individualized joints that fit with little tolerances became possible.

Wood joinery is a connection produced from the material itself, wood. This results in a number of advantages in the joint structure such as having high level of prefabrication and inherit tolerance, assembly efficiency, similarity in dimensions change because of the exposure to changing temperature or moisture and the possibility to design the joint to meet specific tectonic requirements (Tamke and Thomsen 2009). However, the American Institute of Timber (2012, p. 272) points out that wood joinery has limited application in today's wood construction, being restrictive or not applicable for a number of reasons: as it involves large losses of sections due to joint formation process, complicated joinery design when used for large scale, and insufficient capacity for resisting all types of loads.

2. Typology of Wood Joinery

Attempts to classify various joinery types into groups can be found in the works of Gerner (1992) Graubner (1992), Erman (1999) and many others, a seminal study in this area is the work of Zwerger (2012) in which he lists different families of wood joinery found in wood structures, the typology describes how two pieces of wood can be joined together. The proposed taxonomy (figure 1) includes essential joint groups with subtypes in each one. The essential groups are: butt-joint, halved-and-lapped joint, notched joint, tenon joint, end grain to end grain Splicing joint, oblique joint, open mortise and tenon L, T and X joint, edge-to-edge joint, and the L-joint.

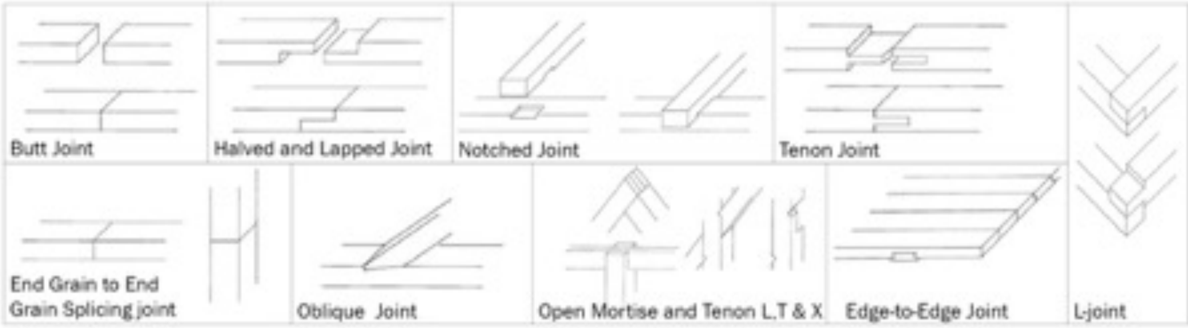


Figure 1: Zwerger's wood joinery classification (Zwerger 2012)

3. Case Studies: Wood Joinery in Complex Structures

it should be mentioned that, for all the selected case studies, integrated design and fabrication tools were employed for the creation of joints to connect wood pieces of complex surface or frame configurations. Since, wood joinery is a material driven and a traditional structural method, this research traces the transformation of this traditional type when aided by the field of algorithmic design modeling in which the algorithm integrates the material, its performance expectations and fabrication constrains into the model.

The majority of these examples are pavilions, the importance of pavilions to the emergence of new architectural systems according to Reichert et al. (2014) is that " In architectural history, pavilions have served as vehicles for developing future concepts of architecture through the employment of new materials, fabrication techniques and design strategies. The architectural pavilion, with its reduced demands in regard to program and permanence, provides a suitable context for exploring construction-oriented innovation".

Regarding the joint typology and due to the customized nature for most of the joints in the following case studies the joint name was kept as it was referred to in the references when existed, renaming or matching joint type with existing typology classification was avoided.

3.1 Scarf and halving joints: Clubhouse at Heasley Nine Bridges Golf Course

Figure 2: Scarf and halving joints for the Clubhouse's wood lattice structure, (Jeska et al. 2014, pp. 113,115,116)

The roof structure for the three storey building is freeform wood lattice structure of glued laminated timber beams in single and double curvature joined with 21 tree-like columns. Roof geometry was developed as a parametric model with the help of defined data of the roof boundary, extensive structural calculations and analysis were needed to generate the beams complex geometries that are composed of multitude individual forms with different radii and changes in direction (Jeska et al. 2014, pp. 109-116).

In this example developed traditional scarf and halving joints were used for the first time in an engineered timber structure, the longitudinal connections between the beams are in the form of scarf joints and the connections at the intersections make use of halving joints. For fabrication the drawings for 3500 beam segments with 476 geometries and 15000 geometrically complex halving joints pieces were automatically generated from the parametric model, using five-axis CNC machine with new software was needed to customize fabrication. Joinery connections were strengthened with additional screw-pressure glue. (Jeska et al. 2014, pp. 109-116).

3.2 Locking-pin Joinery, Tamedia Office Building

Figure 3:(a) Assembling Detail (b)Joinery Detail and (c)Tamedia office Building Wood Frame Structure (Shigeru Ban Architects 2013) (4) Wood joinery detail (Blumer-Lehmann AG 2014)

Tamedia new office building is the first multi-storey building with load bearing structure and joint details made entirely from wood. The load bearing structure was inspired by Japanese wooden buildings; special dowels for wood joinery made of beech plywood connect the structure and transmit loads. The complex locking pin joint was used for three parts that form the load-bearing system: (1) the columns and beams connections; (2) the first floor truss frame; and (3) the roof's rigid frame. The design and assembling of the building required using special design tools for 3D modelling that are not commonly used in wood construction and an extremely precise CNC milling for the frame and joints from glue laminated wood (Antemann 2014).

3.3 Interlocking Finger Joints: ICD/ITKE 2011 Research Pavilion and Landesgartenschau Exhibition Hall

Figure 4: (a) ICD/ITKE 2011 Research Pavilion (b) Finger Joint Detail and (c) Robotic Fabrication of Plates (Institute for Computational Design 2011) (d) Landesgartenschau Exhibition Hall (Menges 2014)

The designs of ICD/ITKE 2011 Research Pavilion and Landesgartenschau Exhibition Hall are based on shared principles for an innovative lightweight timber folded plate system that was developed in by ICD (Institute for Computational Design) and ITKE (Institute of Building Structures and Structural Design). The biomimetic principles found in echinoids such as the sea urchins and sand dollars was translated into a differentiated plate structure with interlocking finger joints (Krieg et al. 2011). The plate structure is distinguished by three plate edges always meet together at just one point, these principles allow the high lightweight structure (built from 6.5 mm thin sheets of plywood) to transmit normal and shear forces (Institute for Computational Design 2011). Advanced computational design and simulation together with robotic fabrication made the automation of repetitive joint details in terms of design and fabrication possible (Menges 2014).

3.4 Interlocking Dovetail Joint, IBOIS Folded Plate Structure Prototypes

Figure 5: from left to right, (a)Interlocking Dovetail Joint illustration (b)Prototype 1 Folded plate shell (c) Prototype 1 during assembly (d)Prototype 2during assembly (e) Prototype 2, spanning 13.5m (Robeller and Weinand 2015)

In a series of studies curried out at the EPEL Laboratory for Timber Construction IBOIS a number of folded plate structure prototypes were designed and fabricated. Robeller and Weinand (2015) proposed the use of dovetail joints for timber folded plate shell structure. No additional adhesive bonding was necessary for the assembly of the self-supported shells. Customized algorithmic tools were developed to generate the physical and virtual prototypes, the automation of repetitive custom dovetail joint geometry details and the machine code programming of the joints. RhinoPython programming interface was used for polygonal mesh processing and joints generation. For first prototype (Figure 5, b & c) was built from 21mm Kerto-Q LVL panels and was fabricated using 5-axis CNC router. The second prototype (Figure 6, d & e) was built from 77mm CLT panels and was fabricated using 5-axis CNC router and KUKA KR250 robot router with an additional linear-axis table for precise 5-axis fabrication. (Robeller and Weinand 2015, pp. 34,55,82,94,116).

3.5 Spline Mitred Butt Joint: Kobra Pavilion

Figure 6: Kobra Pavillion (Manahl et al. 2012)

The design of Kobra pavilion's self-supporting shell structure pavilion is the result of performance driven penalization scheme of continuous double-curved surfaces by discrete planar meshes. After obtaining a form that allows an optimal load transfer the numbers and positions of spline butt joints were determined through a FEM analysis. A custom Grasshopper component was implemented, that imported the results of the analysis and directly generated joint geometries. Pavilion panels were fabricated from cross-laminated timber (CLT) panels; the keys that fit the grooves in the panels were fabricated from Kerto timber material, when fabricating the joint it was very important to line Kerto keys with the main grain direction. Wood panels and joints were cut using 5-axis CNC router and assembled with one component-polyurethane glue (Manahl et al. 2012; Shimek et al. 2012).

3.6 Sliding Slot Joints: Dragon Skin Pavilion, IBOIS modular timber structure prototype and Autobahn Church Interior

Figure 7: (a) Sliding slot joints-Dragon Skin Pavilion (b) dragon Skin Pavilion (Tynkkynen 2012) (c) IBOIS Prototype (Laboratory for Timber Construction IBOIS 2012) (d) and Autobahn Church (Schiffer 2013)

The Freeform Dragon skin pavilion, IBOIS modular timber structure prototype and Autobahn Church interior share a simple joinery detail that was proven effective to assemble these self-supporting structures. The sliding joint that connects bent wood modules in Dragon Skin Pavilion, the V-form folded modules in IBOIS prototype and the wooden ribs in Autobahn Church was achieved by cutting slots from one piece and fixing the other piece into the slot. For the three examples algorithmic procedures generated structure and joinery detailing in addition to fabrication data including nesting and assembly (Margaretha 2013; Nabaei and Weinand 2011; Keskisarja et al. 2012).

3.7 Japanese Chidori Joint: The Prostho Museum, SunnyHills Bakery Building and Starbucks cafe

Figure 8: (a) Chidori Lattice (b) The Prostho Museum (c) SunnyHills Bakery Building (d) Starbucks cafe (Miller 2015, pp. 86-87)

Architect Kengo Kuma designed a several wood pavilions and buildings based on a traditional Japanese joint called Chidori. Chidori lattice is defined as "a traditional technique lacing thin rectangular wood into a lattice by making a special notch in the wood. By using this technique, a strong structure can be created without using any nails, and at the same time, it is possible to dismantle the structure at once"(Kengo Kuma and Associates n.d.). In the three examples Chidori joint is applied in three-dimensional space, for The Prostho Museum, SunnyHills Bakery and Dazaifu Starbucks cafe it was possible for three wood members running along x, y and z axes to pass through the same point. In Prostho Museum Chidori lattice envelopes joints connected orthogonal members together, while in the SunnyHill Bakery and Starbucks cafe buildings parallelogram version of the Chidori was used. Although fabrication was carried out by CNC milling machines, envelop structures were assembled manually by experienced craftsman (Miller 2015, pp. 85-87).

4. Discussions and Conclusion

In the last decades vey rapid transformations have been observed in the realm of architecture through the computational technologies and the changes occurred in architectural design processes and activities from design “recipes” to "design optimization" through these technologies. The potentials of computational design and fabrication technologies, have also altered designers' "material" perception and re-introduced it as one of the main parameters in the architecture of this era.

After examining a number of recently built complex wooden structures it is seen that an integration of computational tools from design to fabrication have been achieved. The execution of these designs was not only possible as a result of advantages of the developed computer numerically controlled machines but also thanks to the advantages of the material itself. From this respect wood has many potentials such as it being a natural, sustainable and easy to manufacture building material, the only building material which is naturally grown from a biological tissue and this why it is considered the only renewable source for building materials. In addition, manufacturing of wood products requires smaller amounts of energy; it is also a recyclable, biodegradable, lightweight, strong and flexible material with environmental and performance benefits.

After examining the selected case studies and within the context of computational design and fabrication techniques, for achieving structural wood joinery in complex structures the related themes emerged that from the analysis can be listed as follows:

1. *New engineered timber materials:* the use of high mechanical and structural load capacity flat or bended panels or frames; such as kerto, CLT, post-formable grade plywood.

2. *Robotic fabrication:* the recent examples show increased use of robotic arms that have no fixed cutting bed, can freely move in three dimensional space and has the possibility of attaching various wood fabrication tools such as shank-type cutter and saw blade as in the fabrication of IBOIS second folded plate prototype (Robeller and Weinand 2015, pp. 57,58)

3. *Building on the knowledge of traditional wood joinery and combine that with other form finding strategies* such as biomimetic design, discretion of free-form surfaces and existing structural systems such as the folded plate system.

4. *In most of the freeform structures using wood joinery didn't lead completely to overcome but it partially substitutes the need to other types of connections* (metal or adhesive etc). In some cases, wood joinery was the connection type for certain parts of the structure such as connecting the inner edges for each module in ICD/ITKE 2011 research pavilion but then assembling the overall structure was done using metal fasteners.

5. *The possibility to feed the computational model with important parameters derived from wood material* properties such as wood bending capacity, grain direction and fabrication tool constrains.

To sum up, architecture based on recipes or prescriptive solutions is not sufficient for an expected architecture of this era and the use of computational design and digital fabrication technologies has changed design and fabrication of traditional materials -especially wood and wood joinery- in the realm of architecture. Together with its inherent characteristics and aided with computational technologies "wood" offers a wide perspective for architects while materializing the complexities of this era. The importance of re-searching new tectonics and materialization technologies and in this regard re-thinking of wood as a “new material” in architecture have potentials to overcome such complexities in design.

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