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REINTERPRETATION OF TRADITIONAL CARPENTRY JOINTS IN CONTEMPORARY WOODEN ARCHITECTURE

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Abstract
The article is devoted to the problem of design and fabrication of joints in contemporary wooden architecture. The CAD/CAM design methodology results in new production and assembly methods used in the creation of novel structural systems. Connections used in structures are often derived from traditional carpentry connections used in a new way. They are reinterpreted and adapted to their new role in new structural systems.
The article presents the results of an analysis of three experimental pavilions conducted in the context of the types of element connections used in their construction. Carpentry joints in traditional architecture were used and fabricated with technologies available at the time and were developed and used in post-beam constructions that utilize large, widely-spaced wood to provide structural support to the building. Timber frame technologies were dependent on mechanical connectors (nails, screws, shear plates, nailed plates). Digital era technologies provide new ways of joining elements according to new structural systems.

Keywords: architecture; wind analysis; CFD; wind tunnel; research based design

INTRODUCTION

Wood has long been used as a construction material, but the properties of solid wood in terms of strength, maximum length and natural wood defects have always been a limiting factor in the implementation of ambitious projects with complex and unconventional geometry. The first civilizations that developed advanced woodworking were the Egyptians and the Chinese. Woodworking is depicted in many ancient Egyptian drawings, and a considerable amount of furniture (such as stools, chairs, tables, beds, chests) has been preserved in tombs. Commonly used woodworking tools included axes, adzes, chisels, pull saws, and bow drills. Mortise and tenon joints are attested from the earliest Predynastic period. These joints were strengthened using pegs, dowels and leather or cord lashings. Animal glue came to be used only in the New Kingdom period. Ancient Egyptians invented the art of veneering and used varnishes for finishing, though the composition of these varnishes is unknown [K. Zwerger 2011].

The fundamental skill of the woodworker throughout the ages has been measured by his ability to join securely—and with elegance—two pieces of wood (hence the English *joiner* and joinery, derived from the Latin *iunctura*). Carpentry wooden joints do not require metal fasteners, but the use of nails and metal plates, such as gussets, makes the task easier. The woodworker needs greater skill and expends more time in making strong joints of wood alone. In the ancient world, wood-to-wood joints were often made without the use of glue, nails, or clamps, although all these aids were known. Vitruvius Polio discusses the origins of wooden architecture and suggests that basic principles resulted from a consideration of Nature herself (Fig. 1) [K. Zwerger. 2011].

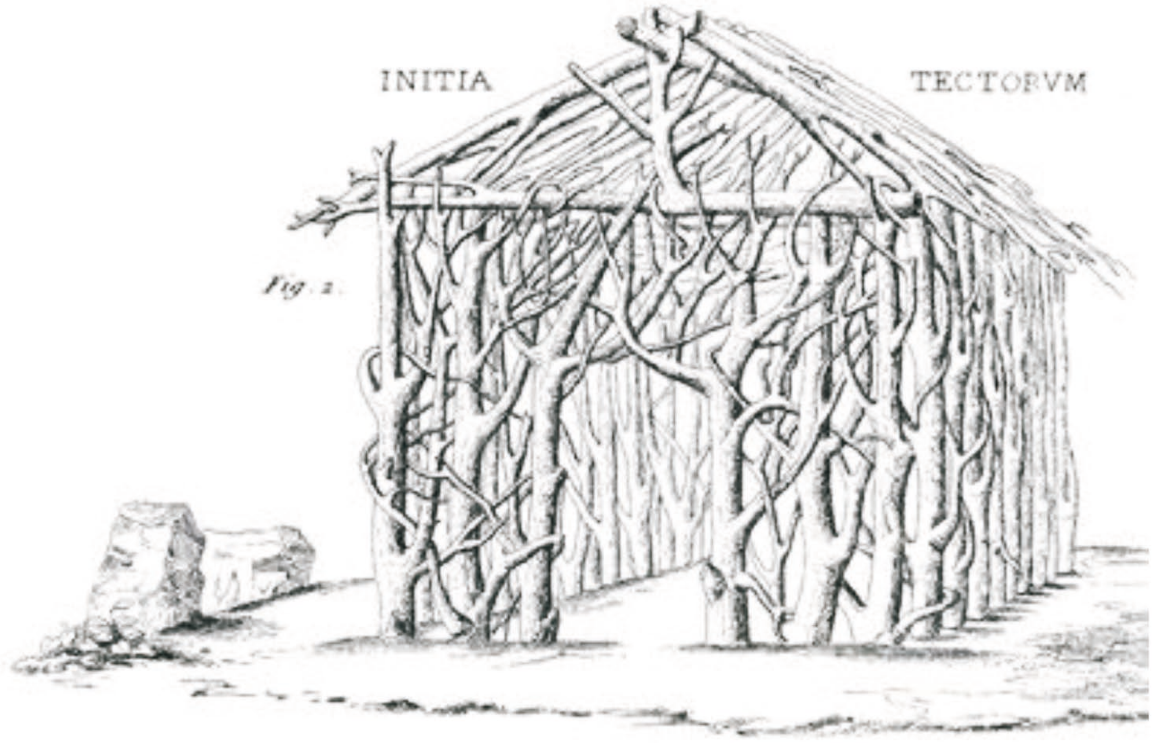


Fig. 1. Johann Rondelet's interpretation of Vitruvius's description of the beginnings of timber construction, J. Rondelet, *Theoretisch-praktische Anleitungzur Kunst zu bauen*; Leipzig; 1833–1835,; source: K. Zwerger 2011.

1. CURRENT RESEARCH CONCERNING CONTEMPORARY WOODEN ARCHITECTURE

The development of CNC technologies allows fabrication of complex architectural forms and structures. Application of wood in structural elements requires discerning particular, anisotropic material properties. Structural timber joints in contemporary wooden architecture often incorporate mechanical connections techniques and reinterpreted traditional joinery. According to S. E. van Nimwegen and P. Latteur: *"Interlocking timber connections that are steel-free and adhesive-free are uncommon in modern construction, but the necessity to maintain cultural heritage alongside the rise in demand for sustainable buildings has revived interest in traditional carpentry techniques, as well as contemporary wood-wood and all-wood connections"* [van Nimwegen, S. E., Latteur, P., 2023]In the article *Historical carpentry joints* the authors say that: *"Historical structures include several hundred different types of carpenter's joints, which were developed through the experience gained by carpenters in a specific area or time-period. Joints are classified in different ways, depending on their form: dowel, glued and notched or their function: extending, increasing dimensions, integrating elements etc."* [J. Jasieńko, T. Nowak, A. Karolak 2014]. This paper summarizes the current state of knowledge related to historical carpentry joints and presents a typology of joints found in timber walls and roof structures.

J.L. Arlet presents the specific examples of the latest solutions presented above which demonstrate that traditional wooden structures and the carpentry joints employed therein remain a model for outstanding contemporary architects and constructors. Conducted research mainly focused on the joints used in construction, as well as their perception. From among many examples, some original and innovative solutions were selected and analyzed [J.L. Arlet 2021].

J. Szewczyk has provided a valuable and multi-disciplinary overview of the development of wooden architecture in a series of articles published in "Builder" [2019a-c]. Three articles comprise its systematization from the perspective of architectural criticism, from a somewhat historical perspective, although focused on the latest phenomena, emphasizing the most interesting current trends. The first part is introductory and generally summarizes the entire phenomenon, first placing it in three categories: material, structure and – briefly – also the aesthetics (form), and indicating those products that determine the current state and the expected (future) horizon of development of modern wooden architecture. The second part is devoted to high-speed wooden construction systems described in a chronological description, starting from their beginnings (11th century AD) to the latest phenomena strictly related to computational technologies and CNC fabrication. The argument also systematizes the approaches to high-speed wooden construction over the last millennium. The third part of the article describes the history of the use of wood in the tallest buildings and systematizes the relevant ancient and contemporary achievements, relating them to four conventional categories of building heights and to analogous records of nature. The significance of the phenomenon was established as a cultural phenomenon in recent years, which for almost a decade has been referred to in the media as "plyscrapers" and increasingly involved in the multilateral relationships between the worlds of business, culture, art and academic science [J. Szewczyk 2019c]. As J. Szewczyk declares: *"The last two decades have brought a revival and development of the idea of wooden architecture at the aesthetic, structural and critical levels… In terms of structural elements, wooden buildings began to be built from volume elements (plates, slabs) instead of columns and beams, but the flexibility of the building material and the stiffness of the connections encouraged engineers to look for new ways to assess the strength of such structures that do not fit into the framework of statically determinate structures. Currently, two groups of methods are being tested: new analytical and computational methods and non-analytical experimental methods based on real measurements. The latter group also includes laboratory seismic tests of wooden buildings, including on 1:1 scale models."* [J. Szewczyk 2019b].

Advanced Timber Structures: architectural designs and digital dimensioning publication from 2016 by prof. Yves Weinand is devoted to research on the use of wood to implement structures characterized by free forms and complex geometry conducted at the Wooden Structures Laboratory (at the Federal University of Technology in Lausanne (EPFL). This unit was founded in 1978 by Prof. Julius Natterer (1938–2021), a leading figure in the field of wooden construction, a pioneer in the use of mass timber, glued timber and nailed timber techniques in the construction of domes and shell structures [Y. Weinand 2016].

The monograph *Advancing Wood Architecture – A Computational Approach* published in 2017, edited by scientists associated with the University of Stuttgart – Achim Menges, Tobias Schwinn, Oliver David Krieg, focuses on the issue of using the inherent properties of wood in the contemporary context of digital design, simulations of behavior in environmental conditions and CAD/CAM digital fabrication technologies. The publication offers a comprehensive overview of new architectural possibilities that are opened up by cutting-edge computing technologies in wooden structures [A. Menges, T. Schwinn, O.D. Krieg 2016].

Digital Wood Design monograph edited by Fabio Bianconi and Marc Filippucci and published in 2018 presents strategies for the digital representation of wooden architecture as a combination of tradition and innovation in design. The articles in the monograph concern advanced digital modeling, with particular emphasis on solutions related to dynamic and generative models [F. Bianconi, M., Filippucci 2019].

2. EXPERIMENTAL PAVILLIONS MADE OF WOOD

The aforementioned academic centers investigate both theoretical and a practical aspects of designing and engineering novel and non-standard wood architecture integrating computational engineering and advanced analysis methods together with fabrication and development of full scale prototypes. An experiment (Latin *experimentum*) is a trial or research performed to confirm or reject a specific hypothesis. In architecture and structural design, these are physical objects of various sizes made at a specific scale. These are material formations that are intended to be a test for the adopted design solutions. Today, parametric modeling tools based on NURBS allow you to efficiently create virtual models at all stages of architectural design, as well as physical models and prototypes in the CAD/CAM system. Experiments with many parameters and the simultaneous action of many different formative forces are almost a new challenge - especially when it comes to assessing various criteria, especially material ones. World architectural universities integrate the processes of: parametric modeling of free-form objects with the numerical production of its components, in search of innovative ways of combining them and to explore the behavior of prototype surfaces in environmental conditions. Below are selected examples of designs that introduced new solutions in building free-form curvilinear structures from wood.

The University of Stuttgart is one of the leading centers dealing with wooden architecture in the era of the digital revolution. The research projects carried out by ITKE and Institute for Computational Design and Construction (ICD) at the University of Stuttgart demonstrate the latest developments in material-oriented computational design, simulation, and production processes in architecture. The Institute for Computational Design and Construction (ICD) is dedicated to the teaching and research of computational design and computer-aided manufacturing processes in architecture. The ICD's goal is to prepare students for the continuing advancement of computational processes in architecture, as they merge the fields of design, engineering, planning and construction.

Zurich's ETH Institute of Structural Engineering (IBK) and Robotic Fabrication Laboratory (RFL) carry out research on designing nonstandard timber frame structures, which are enabled by cooperative multi-robotic fabrication at building scale. In comparison to the current use of automated systems in the timber industry for the fabrication of plate-like timber frame components, the research relies on the ability of robotic arms to spatially assemble timber beams into bespoke timber frame modules.

The University of British Columbia School of Architecture and Landscape Architecture in Vancouver organizes design and construction workshops providing a unique insight into the new opportunities and challenges of advanced design to fabrication processes for timber structures. Numerous experimental pavilions were built: Wander Wood Pavilion (2018), Dragon Skin Pavilion (2019), Zippered Pavilion (2019), C-Shore Pavilion (2020), Mille-feuille Pavilion (2022). These experimental structures are usually assembled without any metal fasteners, drawing inspiration from Japanese and Chinese building traditions.

The subject of this analysis is the study of three pavilions from the years 2014–2022. They were designed and built as full-scale models in leading research projects on wooden architecture and advanced wooden construction. The comparative analysis method was used in order to select characteristic features and types of connections of elements used in the pavilions presented as case studies.

2.1. Case study 1 – ForestPavilion, Schwäbisch Gmünd, Germany 2014

The Forest Pavilion was designed and developed under the supervision of Achim Menges, Jan Knippers and Volker Schwieger at the ICD, ITKE and IIGS Institutes at the University of Stuttgart. The facility was implemented in cooperation with KUKA Roboter, Müllerblaustein Holzbau GmbH, Landesgartenschau Schwäbisch Gmünd 2014 and the forest administration of Baden-Württemberg (Forst BW). The building was built in 2014 as part of the Regional Horticultural Exhibition in Schwäbisch Gmünd in Germany, where it served as an exhibition space [J. Li, J. Knippers 2015].

The architectural form of the pavilion is created by two synclastic dome-shaped surfaces, connected by an anticlastic saddle-shaped area (Fig. 2a–b). The free form of the pavilion surrounds spaces related to its basic functional zones: the reception area, accessible from the south-facing entrance zone, and the main exhibition hall, 6 m high, which can be reached after passing through the narrowing of the building's body. Glass facades on both sides of the building provide views of the surrounding landscape [T. Schwinn 2016]. The shell structure with an area of approx. 245 m² is composed of flat polygonal wooden panels with various geometries connected with finger joints and screws. The wooden panels are arranged according to a changing pattern generated parametrically, which allowed the curvature of the shell surface to be reproduced using flat elements. The Forest Pavilion is a segmented shell structure. The building uses an innovative system of light segment construction made of 50 mm thick beech plywood boards [T. Schwinn, O.D. Krieg, A. Menges 2014].

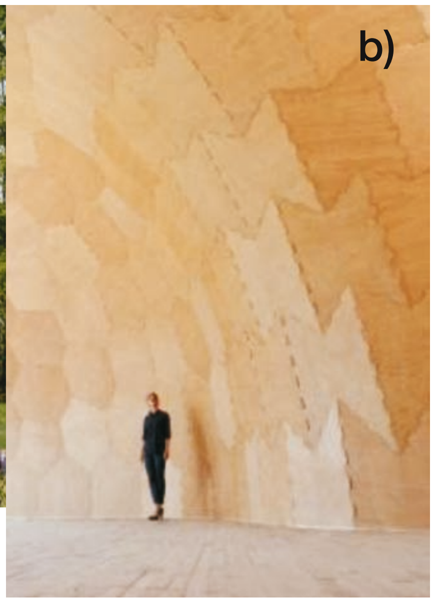


Fig. 2a–b. Forest Pavilion, Schwäbisch Gmünd, Germany 2014; source: J. Li, J. Knippers 2015.

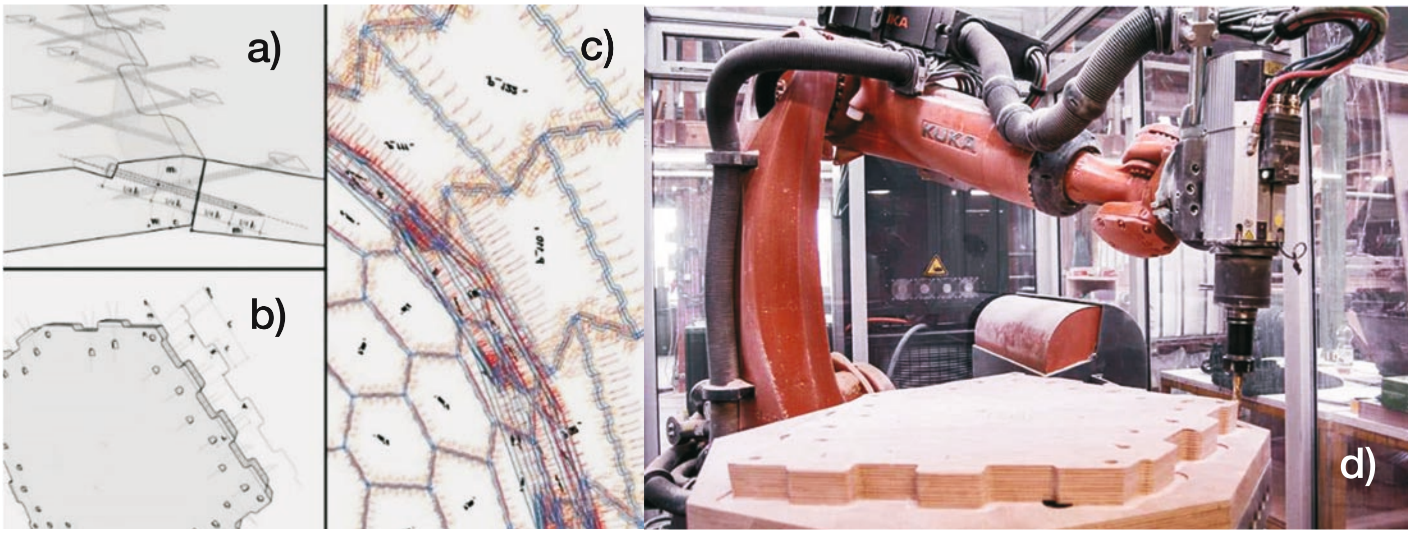


Fig. 3a–d. Forest Pavilion, Schwäbisch Gmünd, Germany, 2014, a–c) finger joint connections strengthened by screws, d) CNC fabrication of structural panels; source: J. Li, J. Knippers 2015.

As in the case of other projects implemented at the ICD, ITKE Institutes at the University of Stuttgart, the inspiration for the construction of the pavilion came from biological systems. Compared to man-made structures, structural systems created by Nature show a much higher degree of morphological diversity. This variation in form and structure is a key aspect for their structural performance and efficient use of material resources. For this reason, the principles of structural morphology and material organization observed in the world of Nature can be successfully transferred to technical applications, including architectural and construction design [T. Schwinn, A. Menges 2015].

The development of the complex plate structure of the pavilion was possible thanks to advanced CAD/CAM computer-aided design methods. The geometry of each component of the segmented shell structure was the result of automated processes of analysis, simulation and optimization of structural work, taking into account material properties and the limitations of CNC robotic production. During the design process, the main emphasis was placed on developing a new collaborative practice based on the digital process loop - from the geometric model to structural analysis and digital CNC production. Robotic production covered all 243 geometrically diverse beech plywood boards for the main structure, as well as prefabricated elements of thermal insulation, waterproofing and cladding (Fig. 3a–d). One of the most important challenges in the project was to make approximately 7,600 unique finger joints using a 7-axis CNC robot [A. Menges, T. Schwinn, O.D. Krieg 2015].

2.2. Case study 2– Robotic Shingled Pavilion, Zurich, Switzerland 2018

The experimental Robotic Shingled Timber pavilion designed under the supervision of scientists from the Gramazio Kohler Research studio was implemented in 2016 at the Federal University of Technology in Zurich (ETH/EPF) as part of a one-year master's degree program in the use of advanced digital support methods in architectural design and manufacturing. Students participating in the course built a full-scale prototype object using an extensive fleet of robotic machines in the ETH laboratories in Zurich. The pavilion is approximately 8 m wide, 10 m long and 6 m high [P. Eversmann 2017]. It is a free-form two-story wooden structure covered with cedar shingles. The supporting structure consists of prefabricated elements in the form of three-dimensional spatial trusses (Fig. 4a–b).

The structure was based on space-trusses of various form but same geometry principle. The structural system based on platform (balloon) frame was adapted to create architectural form of non-standard geometry. Substructure elements built according to this system can perform the functions of a wall, ceiling, slab, roof and staircase. Many prototypes were designed, manufactured and analyzed, which, when improved, led to the final design solution. The structure uses four profiles of solid spruce wood strips, which are connected together with steel bolts and screws. The maximum distance of the truss rods on the external side is limited to 450 mm for surfaces with an angle of inclination in the range of 40–90° to enable the attachment of shingle roof tiles in a way that guarantees the required waterproofness (Fig. 5a–b). Portions of the

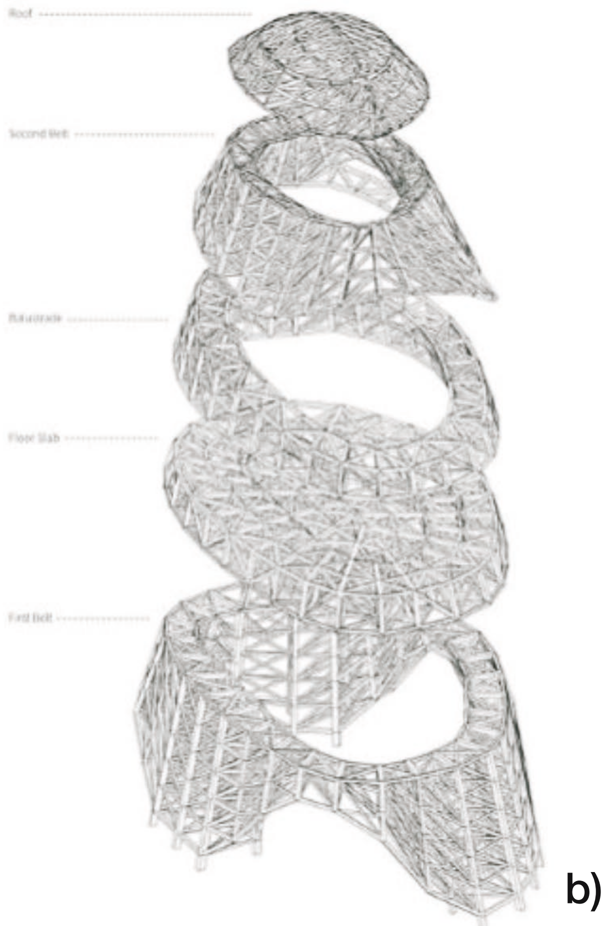
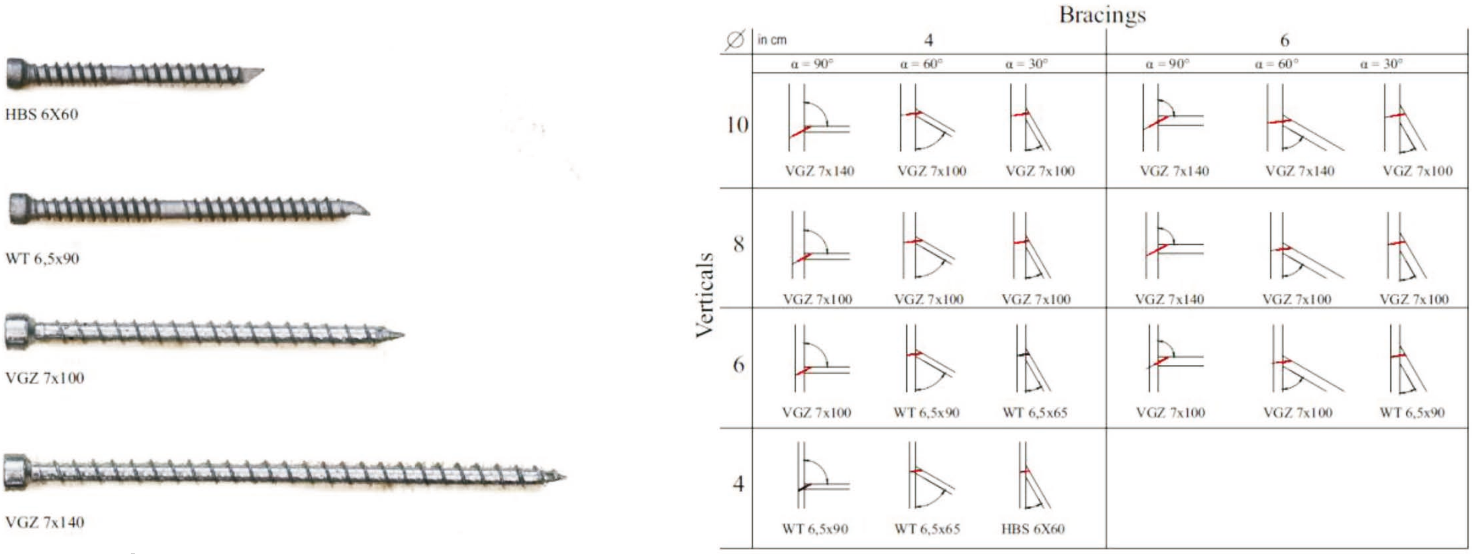


Fig. 4a–b. Robotic Shingled Pavilion, Zurich, Switzerland 2018, a) view of the pavilion; b) the structure of the pavilion; source: P. Eversmann, F. Gramazio, M. Kohler 2017.

surface with less slope, such as the roof, have denser diagonal bracing that allows for double or triple layers of cedar shingles. As Eversmann reports: *"Structural connections since each joint acts in a combination between shear and axial forces, we used full threaded carbon steel screws. Considering the beam's thickness and the angle between the screw axis and the directions of the beams' fibres, we calculated the length and orientation of the screw for each joint. We optimized for four different sizes with similar diameter"* (Fig. 5a–b) [P. Eversmann 2017].

The Shingled Timber Pavilion is the world's first two-story wooden facility built using robots (Fig. 6). The scientific and research intention related to its implementation was to search for new ways of using robotic machines in working with wood. A method of designing a structure consisting of prefabricated modules was examined. The designed geometry of the building's form is composed of expandable surfaces in the form of wavy ribbons creating irregular openings [J. Mairs 2017].



a) b)

Fig. 5a–b. Robotic Shingled Pavilion, Zurich, Switzerland 2018, a) different types of full-threaded screws used for the joints, b) calculation of screw type, length, and angle depending on corresponding geometry and material thickness; source: P. Eversmann, F. Gramazio, M. Kohler 2017.

Fig. 6. Robotic Shingled Pavilion, Zurich, Switzerland 2018, Human-Machine Interaction; source: P. Eversmann, F. Gramazio, M. Kohler 2017.

2.3. Case Study 3 - Mille-Feuille Pavilion, Vancouver, Canada 2022

The temporary Mille-Feuille Pavilion is an experimental facility that shows the potential of parametric design and robotic production to change the way wood is perceived and used in architecture. The object, approximately 3 m wide, 8 m long and 2 m high, is a freestanding partition in the form of a ribbon with a two-curvature unfolding surface (Fig. 7a–b). In the process of designing and fabrication of the pavilion, intensive use was made of digital computational design tools and robotic woodworking tools. The layered structure of the pavilion is composed of 43 overlapping plywood strips, consisting of a total of 150 elements of cut plywood with various geometries.

The name of the pavilion *Mille-Feuille* meaning a traditional French dessert (cake of a thousand petals), refers to the multi-layer construction of the wall-

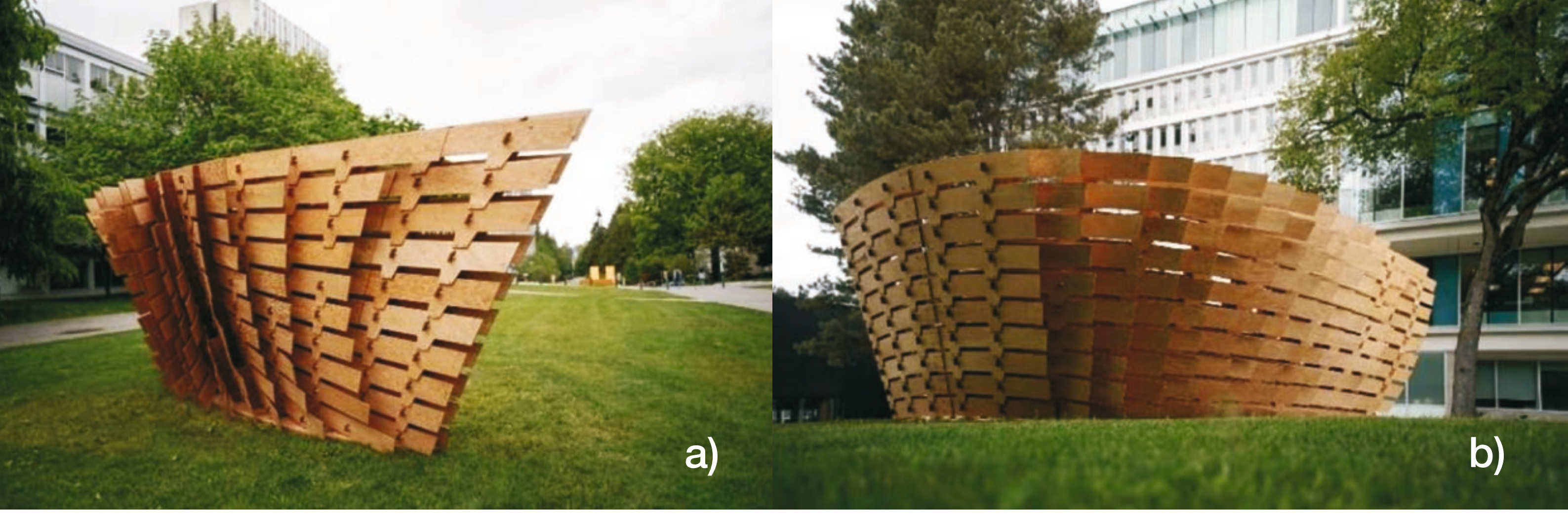


Fig. 7a–b. Mille-Feuille Pavilion, UBC, Vancouver, Canada 2022; source: O. Herwig 2023.

Fig. 8a–c. Mille-Feuille Pavilion, UBC, Vancouver, Canada, 2022, a) robotic CNC fabrication of plywood strips, b) wedging of joints, c) wedged mortise and tenon joint; source: O. Herwig 2023.

shaped structure with variable thickness. The pavilion was created as part of a five-day workshop conducted by scientists: Anna Lisa Meyboom from the University of British Columbia (UBC), David Correa from the University of Waterloo and Oliver David Krieg from the Intelligent City studio. The workshop was held at the Center for Advanced Wood Processing (CAWP) at UBC in 2022 [A.L. Meyboom 2022].

The structure of the Mille-Feuille pavilion was designed as an adaptable system that can be updated to the local availability of materials and production tools. The multi-layer structure is made of strips cut out of waterproof plywood boards. A digital parametric model of the pavilion was used to design the geometry of the elements and their corresponding connections. An important idea was to use the material properties of wood, in this case the flexibility of three-layer birch-alder plywood. In the geometry modeling, the bending limits of each element were taken into account, and if they were exceeded, overlapping of the board strips was used. This principle is a reference to the tradition of building wood, in which the elements remain in a tectonic hierarchy. The use of bent wood is a historically known method of making double curved surfaces (e.g., ship hulls). Plywood, as an anisotropic material, bends effectively in only one direction, one direction of curvature is used as the primary direction of curvature, and the second direction of curvature is provided by connecting elements (spacers and pins) that allow localized bending in the secondary direction [A.L. Meyboom 2022].

In the designed modular system of tensioned elements, each section maintains structural autonomy, which allowed for the prefabrication of parts of the structure. This assembly principle is widely used in the shipbuilding and aerospace industries, where the scale of ship and aircraft hulls poses a challenge similar to that of building structures. The pavilion was made on an 8-axis KUKA industrial robot at the Center for Advanced Wood Processing (CAWP) at UBC. The digital fabrication and assembly of the structural elements took just three days (Fig. 8a-c). The parametrically designed geometry of each individual element ensured precise cutting, machining and identification during assembly. All boards and spacers produced in the robotic production process were assembled in a specific order without the need to use steel connectors, only using wooden connectors and dowels. Pre-drilled holes ensured accuracy when assembling the structural elements. The location of the connecting elements was determined by the form-finding method during the computational design process.

The connections used were wedged mortise and tenon joints which do not require any additional steel connectors. The self-supporting structure needed neither nails nor screws by combining parametric design with robotic fabrication [O. Herwig 2023]. The Mille-Feuille pavilion demonstrates the formal potential of wood's flexibility in the implementation of structures with two-curvature geometry. The combination of traditional materials and digital technologies allows architects to use the material properties of wood while maintaining high design flexibility.

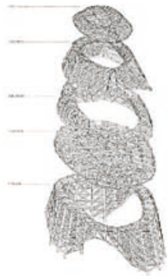
3. ANALYSIS RESULTS

The analysis of three experimental pavilions designed between 2014 and 2022 showed a deep integration of geometry of form, material properties and manufacturing technologies (Tab. 1).

The analysis revealed that all pavilions are characterized by architectural free-form based on doubly curved surface. The free-form surface is modeled parametrically using NURBS techniques. The dynamic development of digital technologies observed since the end of the 20th century is changing the way we think about architecture. The development of modeling software based on NURBS and scripting languages has made programming an integral part of an architect's work. The potential of parametric design and digitally aided manufacturing technology has also changed designers' perception of the material and reintroduced it as one of the main parameters of the design process.

The analysis of the experimental pavilions has shown that the material most often used to construct the presented objects are building materials based on engineered wood products, such as plywood. Wood-based panel boards are a composite material, produced industrially by gluing an odd number of thin layers of wood. Depending on its thickness, thin-layer or thick-layer plywood is produced. Native wood species are used for production, such as alder, birch, beech pine and wood from exotic trees. The strength and elasticity of plywood depends on the number of layers of wood used during its production. Moreover, the strength parameters also depend on the direction of the fibers in the outer layers and on the direction of the load in relation to the board surface. Wood-based materials in the form of boards: plywood, chipboard and MDF fiberboard, laminated veneer wood (LVL), cross-laminated wood (CLT) are quasi-orthotropic materials. Their strength properties change in thickness - along the Z axis, while in the plane of the plate (in the XY plane) they are approximately constant.

Tab. 1. Analysis of experimental pavilions

Pavilion name	FOREST PAVILION	SHINGLED TIMBER ETH	MILLE-FEUILLE PAVILON
Location	Schwäbisch Gmünd, Germany	Zurich, Switzerland	Vancouver, Canada
Year	2014	2016	2022
Design	University of Stuttgart ICD, ITKE IIGS	Swiss Federal Institute of Technology in Zürich (ETHZ)	UBC SALA (School of Architecture & Landscape Architecture)
Architectural form	Free-form surface	Free-form surface	Free-form surface
Structure type	 Double curvature segmented wooden shell	 Double curvature hybrid structure	 Wall-shaped double curvature layered shell
Substructure type	 Hollow building segments	 Matching space-frame substructures	 Plywood strips
Structural material	Engineered wood product – birch plywood	Construction timber (spruce)	Engineered wood product – birch-adler plywood
Robotic fabrication	5-axis KUKA KR QUANTEC industrial robot	robotic setup of two large-scale ABB industrial robots on a linear track	8-axis industrial robot at the Centre of Advanced Wood Processing at UBC
Human Machine Interaction	-	+	-
Construction time	2 months	5 weeks	3 days
CONNECTION TYPES	 **INTERLOCKING EDGE JOINTS STANDARDMECHANICAL CONNECTORS (SCREWS)**	 **STANDARD MECHANICAL CONNECTORS (SCREWS)**	 **WEDGED MORTISE AND TENON JOINT**
Relation to tradition of wood architecture	Reinterpretation of woodworking joint	Reinterpretation of steel connectors technology	Reinterpretation of carpentry joint

Source: prepared by the author based on: J. Li, J. Knippers 2015; P. Eversmann 2017; O. Herwig 2023.

New material and manufacturing options open new ways to innovative structural solutions. The experimental pavilions utilize new structural solutions. In 21st century architecture the surface of the architectural form is activated and serves as the covering skin of the building but acts structurally [K. Januszkiewicz 2013]. Each of the analyzed pavilions represents a different structural system:

- Segmented wooden shell,
- Hybrid structure,
- Wall-shaped layered shell.

Each analyzed structural system also has a different subsystem in the form of:

- Hollow building segments,
- Matching space-frame substructures ,
- Plywood strips.

The analysis in terms of structural connection revealed following connection types:

- Interlocking Edge joints,
- Standard mechanical connectors (screws),
- Wedged mortise and tenon joint.

4. REINTERPRETATION OF CONNECTIONS OF CONSTRUCTION ELEMENTS

Free-form wooden structures require a much higher number of joints, much greater than in conventional post-and-beam structures. This is due to the presence of a much larger number of elements that are connected to neighboring elements on the edges or side surfaces. New structural solutions are commonly based on engineered wood materials which are becoming more and more common and require new types of connections. These joints have not been previously used in the tradition of building with wood (interlocking edge joints), have been used in a modified form (pegged mortise and tenon joint) or have used existing technology (mechanical connectors) for structural joining.

4.1. Interlocking edge joints

A box (finger) joint is a basic woodworking corner joint made by cutting offset profiles in two pieces of wood and interlocking the resulting rectangles or “pins” together. These types of joints have been widely used in woodworking, carpentry and furniture manufacturing (Fig. 9a–c). Instead of using one connection as it was logical in connection of two elongated elements like post and beam in traditional construction, a new way of use is to arrange finger, box or dovetail notches rhythmically on the edges. The pieces are cut at an angle, creating finger-like projections that interlock with each other. Since these profiles are cut straight, they can be assembled directly into one another. The joints are then

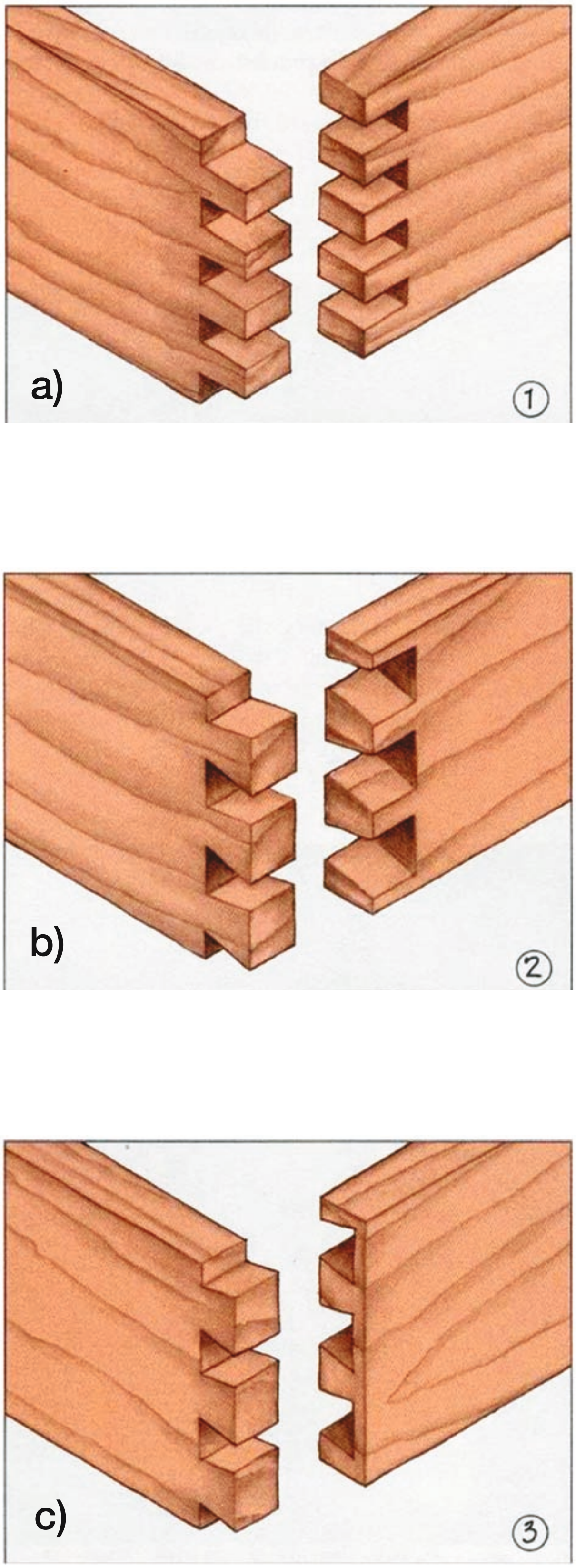


Fig. 9a–c. Interlocking edge joints of board elements in woodworking, a) box joint, b) dovetail joint, c) half-blind dovetail joint; source: Woodworking Archive 2023.

glued to create solid, seamless pieces of wood. Interlocking wooden joints are a material driven traditional structural method that is used in complex wooden structures. Nowadays they are frequently used in computationally designed and digitally fabricated wooden structures.

4.2. Mechanical connectors

Connecting wooden elements without using steel connectors requires extensive knowledge and experience. The use of metal connectors in wooden structures ensures faster assembly, saves construction material and guarantees the stiffness of connections and stability of the structure (Fig. 10). A wide range of available system solutions (nails, mounting screws, profiles, clamps, nail plates, etc.) allows to make connections for various applications. The system of connecting wooden and wood-based structural elements using nail plates was introduced in the United States in the 1960s and is increasingly used in modern construction [M. Major, J. Różycka 2013]. All connecting systems are made of hot-dip galvanized steel sheet or stainless steel, which protects them against corrosion.

4.3. Mortiseand tenon joints

Mortise and tenon joints connect structural elements, usually in an L- or T-shaped arrangement, with an angle between the connected elements from 45° to 90°. A socket is made in one joined element, in which a tenon made in the other element is placed. It is important to match the contact planes between the elements. Such connections are often pinned. Mortise and tenon joints are strong and stable joints additionally connected by either pegging, gluing or locking into place. There are many variations of this type of joint, and the basic mortise and tenon has two components: the tenon, formed on the end of a member generally referred to as a rail, fits into a square or rectangular hole cut into the other, corresponding member (Fig. 11a–c). The tenon is cut to fit the mortise hole exactly. It usu-

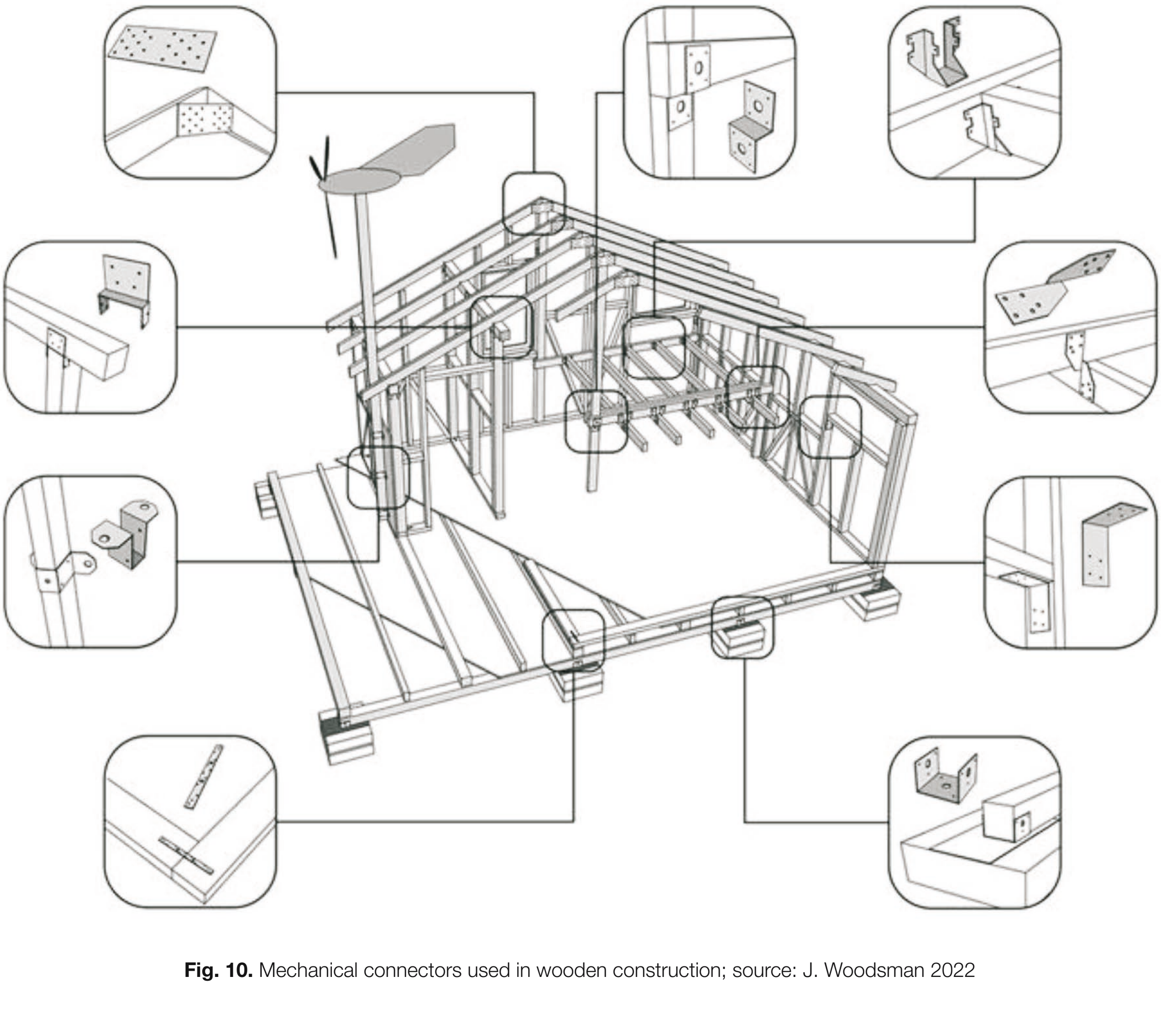


Fig. 10. Mechanical connectors used in wooden construction; source: J. Woodsman 2022

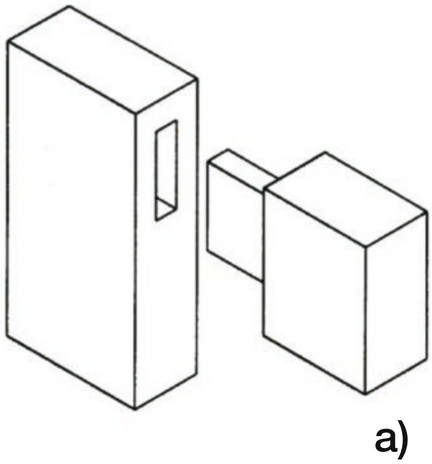
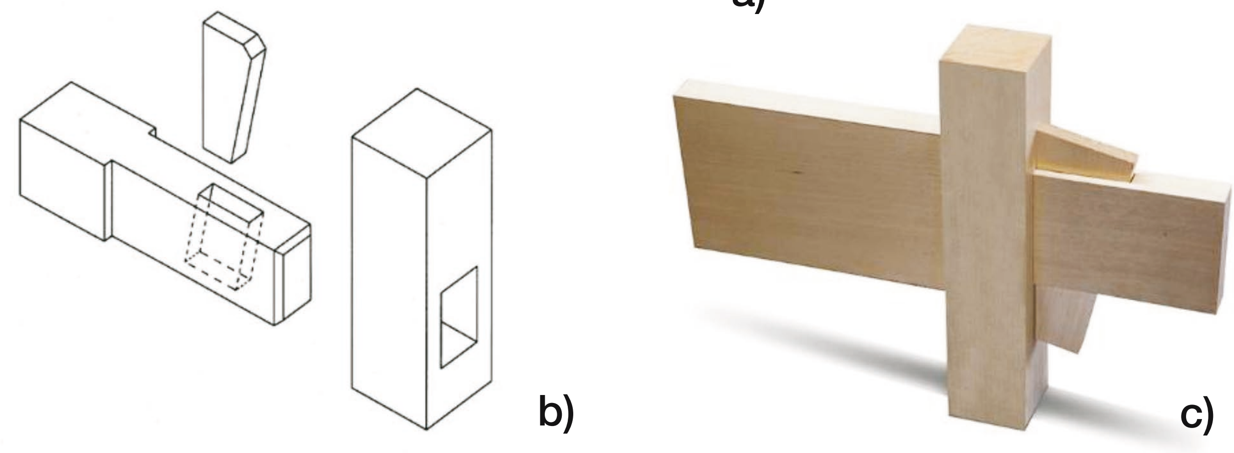


Fig. 11a–c. Mortise and tenon joints, a) regular joint, b–c) wedged joint; source: PuuProffa 2021b.



ally has shoulders that seat when the joint fully enters the mortise hole. The joint may be glued, pinned, or wedged to lock it in place. One drawback to this joint is the difficulty in making it because of the precise measuring and cutting required. In its most basic form, a mortise and tenon joint is both simple and strong [J. Woodsman 2022; Woodworking Archive 2023].

The wedged joint is a traditional connection with a wedge pushed into the hole of the mortise piece (Fig. 10b–c). The hole must have the same inclination as the wedge. The wedge angle must be under 20° so that the wedge will stay tight.

CONCLUSIONS

The development of computer technologies has opened new paths for design based on parametric modeling and digital manufacturing. This potential is making a decisive contribution to renewing the interest of designers in the use of wood. Although wood is one of the oldest building materials, in recent years many innovations have influenced production techniques and design tools that have paved the way for new formal, aesthetic and structural solutions that can fill the fields of application of this material.

New material characteristics of wood-engineered materials in conjunction with the design and manufacturing aspects in the digital CAD/CAM process chain opened up new possibilities for formal expression. However, due to the high cost of implementation of free-forms in architecture the curvature of the surface is most often approximated by linear or flat elements. The architectural form of the buildings is therefore divided into smaller elements, which facilitates the manufacturing and assembly process. The conventional carpentry joints developed in the past most often do not meet strength requirements and are not applicable to forms of geometric complexity. These joints were developed for connections in post and beam and frame structures used in wooden structures.

New structural solutions for complex geometry based on engineered wood materials are becoming more and more common and require new types of connections. In modern wooden structures new kinds of connections referring to historical solutions are successfully used in a reinterpreted and modified way.

These joints have either not been previously used in the tradition of building with wood (interlocking edge joints), are used in a modified form (pegged mortise and tenon joint) or are using existing technology (steel connectors) for structural joining.

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