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Transparent wood: a new innovative material for architectural restoration

The potential of transparent wood in replacing traditional materials

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"Study the past if you would define the future."
温故而知新，可以为师矣

– Confucius

Temple of Confucius in Beijing.
From my trip to China in April, 2025.

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PREFACE

The decision to dedicate this thesis to the study of transparent wood arose from a deep fascination with its innovativeness and architectural potential. As an emerging material at the cornerstone of bio-based materials and advanced engineering, transparent wood represents one of the most compelling developments in contemporary material research. Its novelty, coupled with the scarcity of architectural studies addressing its long-term performance, made the topic not only intriguing but also timely and relevant. I was motivated by the idea of exploring a material whose full implications for architecture are only starting to be understood, and whose future applications may profoundly influence the way we design and build.

The purpose was to imagine a future in which transparent wood could be implemented in real architectural contexts, especially in the restoration interventions, and to contribute to the knowledge required to support this transition. Positioned within a wider and continuously evolving scientific field, the research will undoubtedly progress in the coming years as the material moves closer to practical adoption.

My contribution focuses on the assessment of transparent wood's durability in outdoor conditions, a critical factor for understanding its suitability for the built environments. By preparing and testing samples under controlled UV exposure, this work provides initial insights into the material's long-term behaviour. These findings serve as a basis for future investigations and for imagining, through unrestrained ideas, its potential applications.

More broadly, this thesis also reflects on the importance of revisiting past design solutions through the lens of new technologies and innovative materials. Looking back does not imply negating the original design intent; rather, it allows to reinterpret it and to enhance it in ways that were not previously possible. Transparent wood exemplifies this mindset: it invites architects and researchers to challenge established conventions and to envision alternative paths for the built environment.

I. WOOD AS A MATERIAL

Wood is a living historical archive.

Forests cover more than 30% of the land on Earth (Fig. 1) and provide a renewable and sustainable resource. [1] They are furthermore essential in regulating biodiversity and carbon sequestration. When sustainably managed, forests offer a continuous supply of wood biomass, as harvested trees are replanted to preserve ecological balance and long-term resource availability. [2]

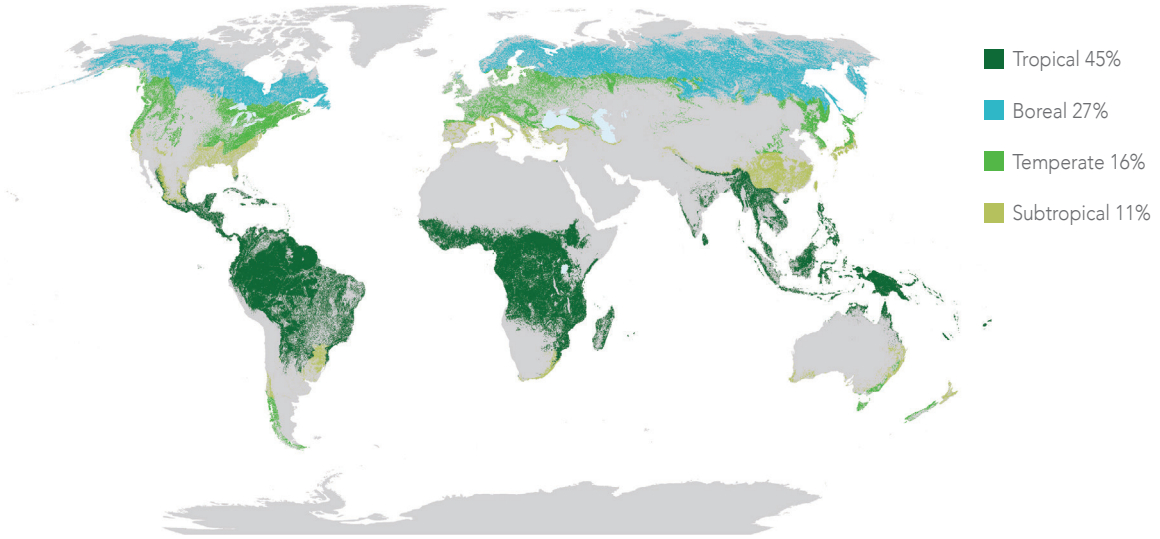

Figure 1. Global distribution of forests by climatic domain. Percentages may not sum due to rounding. Adapted from [3]

Wood is then one of the most abundant bio-materials on Earth and has been ubiquitously used by humanity. It has served in construction, tool-making, furniture, and as a source of fuel. [1] Its structural and functional complexity underpins its versatility and explains the long-standing role in technological and cultural advancements. [4] Apart from its utility, wood can even be regarded as a living historical archive because it records information about its environmental and biological conditions over time. [5] [6]

The context in which wood is reconsidered today is shaped by the consequences of the Industrial Revolution, which triggered an exponential increase in atmospheric carbon dioxide (CO_2) due to fossil fuel consumption. In 2020, the building sector was responsible for 37% of total global CO_2 emissions, the largest share among all sectors, with building operations accounting for most of the energy demand and related emissions. [7] This highlights the urgent need to replace fossil-based, finite materials with renewable and sustainable alternatives in construction and beyond. [2] The notion of sustainable development, introduced by the UN World Commission on Environment and Development in the 1987 Brundtland Report, is defined as *"the development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. [8] This principle underscores the necessity of shifting to renewable resources, expanding the use of bio-based products, and committing to long-term environmental protection.

Wood exhibits a significant potential being at a cornerstone of both natural ecosystems and human engineering. The central challenge of the 21st century is to develop sustainable and high-performance materials that not only match but surpass the performance of fossil-based alternatives. [2] With its abundance, renewability, and inherent structural advantages, wood holds promise in supporting this transition toward a sustainable future.

I. a. WOOD HIERARCHICAL STRUCTURE

Wood is a natural composite material

Wood can be considered a natural composite material due to its three main components: cellulose, hemicellulose, and lignin. Each of these biopolymers has distinct properties under a structured form and together they determine the mechanical and overall functional behaviour of wood. [1]

Because wood properties are also influenced by the tree species, it is useful to first distinguish between softwood and hardwood, whose characteristics are summarized in Table 1. Hardwood comes from angiosperm trees, typically broad-leaved, deciduous species such as oak, beech, walnut, and maple. It presents a complex anatomical structure, containing vessels and fibers, which together provide it with a distinct grain pattern and varied texture. Softwood comes from gymnosperm trees, primarily conifers such as pine, spruce, fir, and cedar. It is characterized by a simpler anatomical structure, composed mainly of tracheids, which perform both water and nutrients conduction and structural support. Hardwoods are denser, stronger, and more durable than softwoods, and typically contain 40-60% cellulose, 24-40% hemicellulose, and 10-25% lignin, while softwoods contain 45–70% cellulose. [9]

	 HARDWOOD	 SOFTWOOD
Botanical origin	*Angiosperm trees (deciduous)*	*Gymnosperm trees (evergreen)*
Leaves	*Broad, typically shed annually*	*Needle-like*
Examples	*Oak, beech, walnut, maple*	*Pine, spruce, fir, cedar*
Main characteristics	- *High density* - *Heavy* - *Slow growth rate* - *Strong and durable* - *Difficult to cut and shape* - *Expensive*	- *Low density* - *Lightweight* - *Fast growth rate* - *Soft and less resistant* - *Easy to cut and shape* - *Less expensive*
Cellular structure	*Vessels (transport) and fibers (support)*	*Tracheids (transport and support)*
Cellulose content	*40-60 %*	*45-70 %*
Aesthetics	*Grain pattern, dark colours*	*Uniform pattern, light colours*
Uses	*High-end furniture, flooring, musical instruments*	*Construction, base furniture, decking*

Table 1. Comparison of key properties and characteristics of hardwood and softwood.

Among these three components, cellulose is the most abundant one, forming the main framework of the nanostructure. It consists of long linear chains of anhydro-glucose units (Fig. 2), a direct product of photosynthesis, assembled into elementary fibrils (3–5 nm), which further bundle into larger aggregates (15–50 nm). These fibrils present both crystalline and amorphous regions: the crystalline domains are made by stacked cellulose chains parallel with each other and bound by inter- and intra-hydrogen bonds, while the amorphous domains by abundant twists and distortions that alter the ordered arrangement. Failure of wood may arise from the sliding between these molecular chains, and so the degree of polymerization of the cellulose chains plays an important role in dictating the strength and toughness of wood. [1]

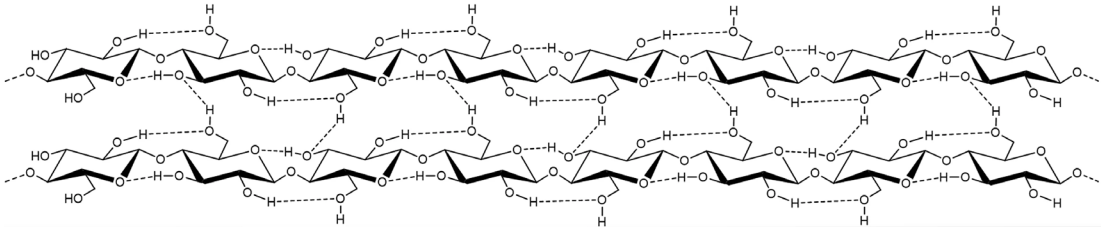

Figure 2. Cellulose. [10]

Hemicellulose is instead amorphous and highly hydrated, forming branched heterogeneous polysaccharides. Among these, softwood hemicellulose is rich in glucomannan, while hardwood contains mostly xylan (Fig. 3). [11] Its amorphous nature allows it to interact with both lignin and cellulose, forming a cross-linked network.

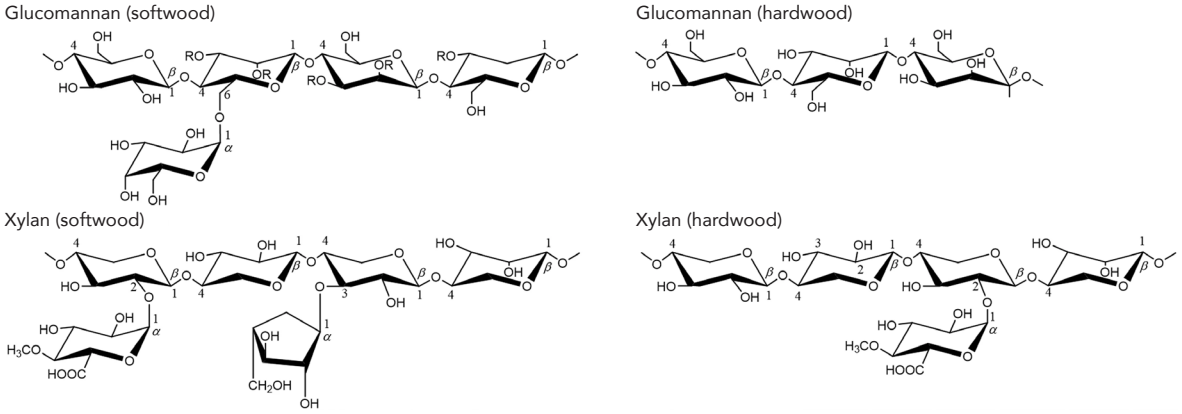

Figure 3. Hemicellulose. Adapted from [10]

Finally, lignin (Fig. 4), whose name comes from the Latin word *lignum*, meaning wood, is an amorphous, aromatic polymer composed of three building units, guaiacyl, syringyl, and p-hydroxyphenyl, with syringyl dominating in hardwood and guaiacyl in softwood. [11] It protects against UV radiation, pathogens, and insects, and provides hydrophobicity to cell walls, thus helping the wood tissue transport water, nutrients and photosynthesis products in an efficient way, playing both biological and structural roles. Furthermore, it provides stiffness even in the absence of turgor pressure, that is the hydrostatic pressure exerted by water inside a cell against its wall, which causes the cell to expand. [9]

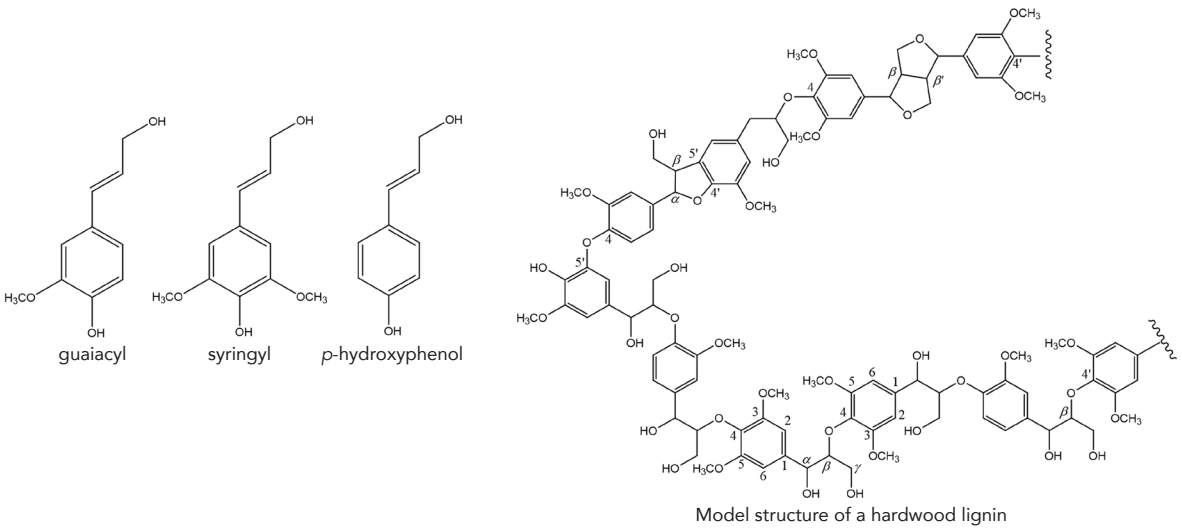

Figure 4. Lignin. Adapted from [10]

Wood's hierarchical structure starts at the millimetre scale with the annual growth rings, composed of alternating earlywood and latewood. Earlywood, with large lumens and thin cell walls, forms at the beginning of the growing season and is specialized for water and nutrients transport, while latewood, with small lumens and thick cell walls, forms later in the season when growth slows and provides mechanical strength. Depending on the climate of the belonging region, the transition between earlywood and latewood can be sharp. [12] These changes result in alternating density and stiffness across the radial section, giving rise to a periodic modulus and strength profile. The annual rings, often referred to as the tree's diary, reflect the climatic and environmental conditions; for instance, wide rings may indicate rainy seasons, and, in recent decades, increased CO_2 levels and higher temperatures have enhanced growth rates. [5] The study of growth rings, known as dendrochronology, uses these patterns to reconstruct past environmental conditions. [6]

Moving forward, at the cellular and tissue level, wood consists of several hollow fibers, called lumens, mainly aligned longitudinally with the tree stem (Fig. 5). Adjacent cells are bound together by the middle lamella, which is rich in lignin. [1] The cell wall is organized into several levels: the primary wall and three layers composing the secondary wall (S1, S2, and S3). The primary wall is the outer and is formed by a single layer of randomly-oriented cellulose microfibrils. Then, among the secondary wall, the S2 layer represents about 80% of the cell wall thickness and is the most mechanically significant. [2] Here, cellulose fibrils are aligned nearly parallel to the fiber axis, with their orientation defined by the Microfibril Angle (MFA). A small MFA provides an excellent mechanical performance with high stiffness, while a larger MFA determines flexibility and impact resistance. [12] Fibers are typically 1-3 mm in length and 20-50 μm in diameter, with thickness of a few micrometres. [4] Tracheids dominate in softwoods, comprising over 90% of their structure, and vary in size and wall thickness depending on whether they function as earlywood (transport) or latewood (support). Hardwoods, in contrast, evolved specialized vessels for transport and fibers for support, making them more efficient in most climates but also more porous due to large lumen diameters and thin cell walls. [1]

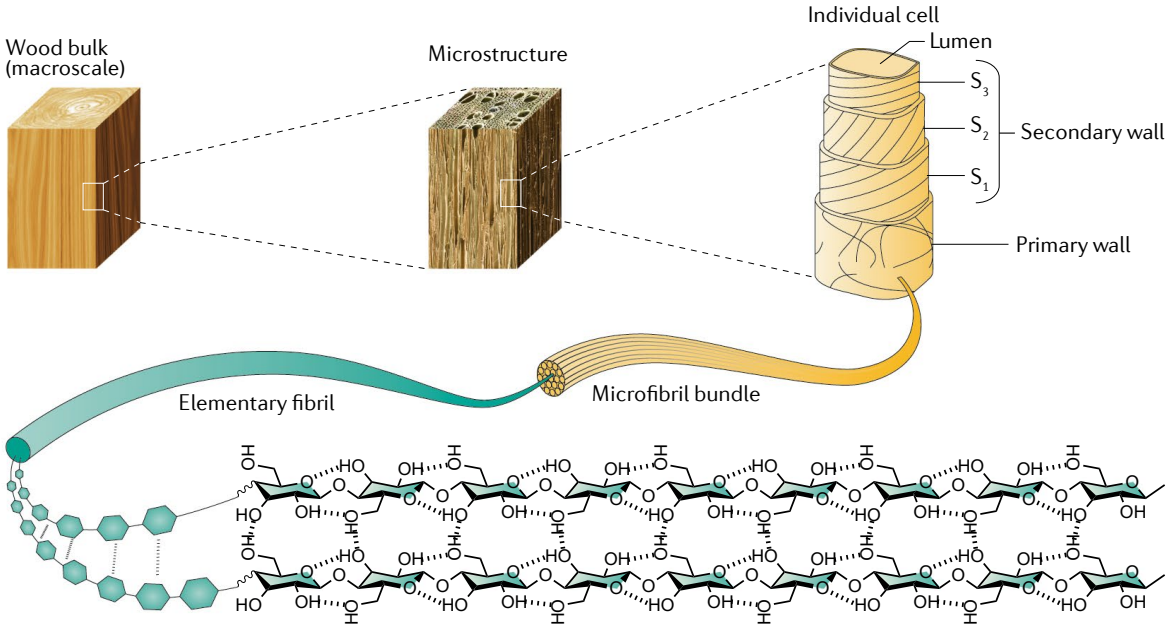

Figure 5. Hierarchical structure of wood and cell wall levels. Reproduced from [1] under the licence ID 1673421-1.

At the nanoscale, instead, wood is structured with stiff cellulose nanofibrils, of only 2–4 nm in diameter and few micrometres long, which together form microfibrils, embedded in a hydrated matrix of hemicellulose and lignin (Fig. 6). [1] Lignin is mainly located in the secondary wall and middle lamella, where it functions as a binder, holding fibers together and forming the Lignin–Carbohydrate Com-

plex (LCC). This complex is rich in covalent and hydrogen bonds with cellulose and hemicellulose, giving rise to high adhesion energy and strengthening the overall wood matrix. [10] The fibril bundles in the S2 layer are almost aligned with the axis with small MFAs, giving wood its anisotropic mechanical performance. [9]

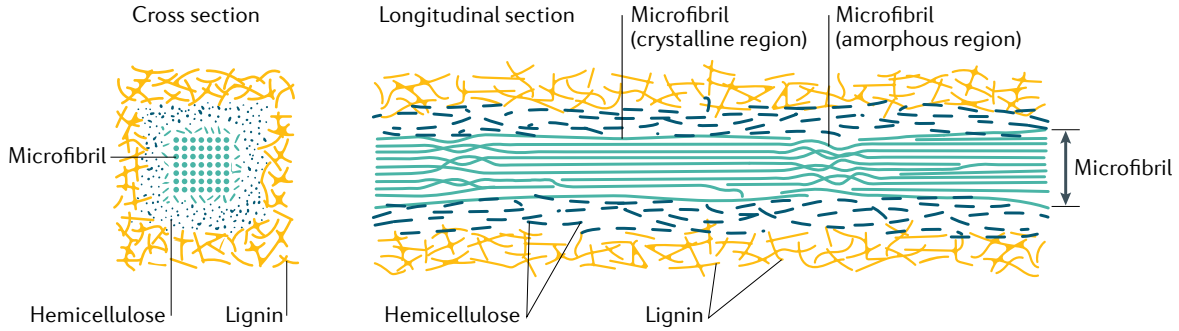

Figure 6. Microfibril cross section. Reproduced from [1] under the licence ID 1673421-1.

The different scales of wood's hierarchical structure may be summarized as in the following table:

	MAIN STRUCTURAL FEATURES	DIMENSIONS	PROPERTIES
Macroscopic (millimetre to centimetre)	*Annual growth rings composed of alternating earlywood and latewood*	*Width varies with environmental conditions*	*Early wood has large lumens and thin cell wall for water transport; latewood has small lumens and thick cell wall for mechanical support*
Tissue/cellular (micrometre to millimetre)	*Hollow fibers almost aligned longitudinally with the tree axis*	*Length 1-3 mm* *Diameter 20-50 µm*	*Microfibril Angle (MFA) determines the mechanical performance*
Cell wall (micrometre)	*Layers (out-in): middle lamella, primary wall, secondary wall (S1, S2, and S3)*	*Thickness few µm*	*Middle lamella is rich in lignin and binds the cells together; S2 layer in secondary wall represents 80% of cell wall thickness and provides support*
Nanostructure (nanometre to micrometre)	*Cellulose nanofibrils embedded in a hydrated matrix of hemicellulose and lignin*	*Length few µm* *Diameter 2-4 nm*	*Lignin-Carbohydrate Complex (LCC) rich in covalent and hydrogen bonds* *Fibril bundles in the S2 layer have small MFAs, providing anisotropy*

Table 2. Summary of the different scales of the wood hierarchical structure.

The differences between softwoods and hardwoods in the wood tissue structure are strongly related to their evolutionary and anatomical development. Softwoods are mostly composed of tracheids, while hardwoods have distinct vessels and fibers according to the functions, marking a competitive advantage in water transport and mechanical functions. Structural diversity among species arises mainly at the cellular and tissue level, leading to different densities. Taking as an example two different hardwood species, low-density balsa (80-300 kg/m^3) has large vessels (~250 µm diameter) and fibers (~40 µm diameter), and very thin walls (~1 µm), while high-density birch has smaller vessels (~80 µm) and fibers (~20 µm), and thicker walls (~3 µm). [2] However, despite these differences in porosity and density, the fundamental layered structure of the cell wall is remarkably conserved. [2]

On side to the isolated and collective mechanical behaviour of the major components of wood, as well as the interaction between them, the porous nature of wood plays an equally critical role in its performance. Wood exhibits multiscale porosity, ranging from microscale voids (lumens) to pits connecting adjacent cells, down to nanoscale pores within cell walls. [1] The porosity percentage varies with density and is essential for water and nutrient transport, as well as for controlling the thermal, mechanical, and optical properties. This hierarchical porosity also provides pathways for

multiphase transport of ions, molecules, gases, and liquids, and enables interactions across multiple energy scales, including photons, phonons, microwaves, and acoustic waves. [1] Wood's anisotropy is another defining property. With most of the cells aligned vertically and the remaining forming horizontal rays, wood exhibits direction-dependent mechanical and physical behaviours. This anisotropy influences both performance and aesthetics, meaning that the way wood is cut from the log affects not only its strength but also the visual appearance. [1] Finally, the multiscale, hierarchical organization of cellulose, hemicellulose, and lignin, combined with the porous, anisotropic architecture of fibers, vessels, and growth rings, provides wood with a unique balance of strength, fracture toughness, stiffness, and energy dissipation. These properties are strongly tied to the structural synergy between crystalline cellulose fibrils and the amorphous hemicellulose-lignin matrix, thus making wood a natural composite with remarkable mechanical efficiency and multifunctionality. [13]

I. b. PROPERTIES OF WOOD

Understanding the structure-property relationships of natural wood is necessary to make informed structural and chemical modifications, thus controlling the properties of the material. For example, the anisotropic nature of wood leads to anisotropic properties in terms of mechanical performance, water transportation, thermal conductivity, and optical characteristics. Furthermore, being a hygroscopic material, wood readily absorbs and desorbs water from its environment, which significantly influences its mechanical properties, dimensional stability, and overall performance over time. [2]

I. b. 1. MECHANICAL PROPERTIES

The mechanical response of wood strongly depends on the loading direction (Fig. 7), given its anisotropic nature. Along the longitudinal direction, also called axial direction, the best mechanical properties are recorded because the axis is parallel to the fibers. On the other hand, radial and tangential axes are perpendicular to the fiber direction, with the radial axis normal to the growth rings, providing ductility. [12]

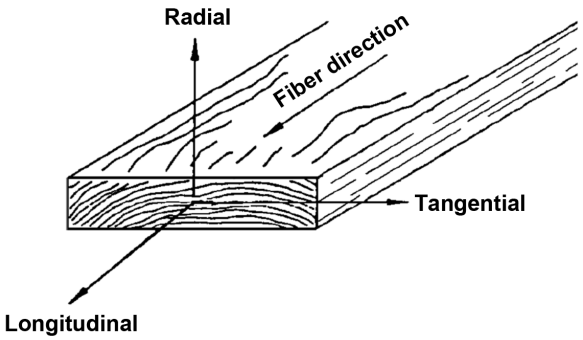

Figure 7. The three main axes of wood with respect to fiber direction. [14]

Aside to this anisotropic nature, the complex hierarchical cell structure is another factor that influences the mechanical performance. At the bulk wood and tissue level, the density, expressed as the ratio between mass and volume, is the dominant factor that determines the mechanical properties. At the cell wall level, the orientation of the cellulose nanofibrils (MFA), the number of hydrogen bonds, and the interactions between cellulose and the surrounding polymer matrix are instead of particular importance. [15] The relative proportion of wood components, and in particular lignin, also affects the mechanical performance: older and denser wood shows enhanced stiffness and compressive strength, while younger wood with lower lignin content tends to be more flexible and mechanically weaker. [15]

Under mechanical stress, the deformation of wood consists on various processes at the cell wall level, including fibril sliding and cellulose-hemicellulose interactions with the repeated breaking and reforming of hydrogen bonds. [1] The sliding failure of a wood material can be captured by the energy variation. The peak of energy curve indicates that the hydrogen bonds are stretched to the maximum, while the drop of energy occurs when these bonds break. New hydrogen bonds can be readily formed when the new hydroxyl groups come close to each other, and this happens in new configurations. [11] Such a cascade of events gives rise to the zig-zag profile of the energy curve, which adds to the work needed to fracture the wood, revealing the capability of wood to actively resist failure and a unique toughening mechanism in modified wood and cellulose-based materials. [1] The cellulose elementary fibrils exhibit outstanding material properties for a broad range of applications, demonstrating a tensile strength as high as 7.5 GPa in the crystalline form, which is higher than most of metals and alloys. [7]

Even if the mechanical properties of wood benefit from the cellulose nanofibrils and hydrogen bonds, the natural occurrence of pits makes them defects from a structural-material perspective, even if they serve essential biological functions in trees. At a macroscopic level, instead, knots are the main defects, which come from branches grew from the trunk and limit large-scale strength properties. Depending on the considered thickness and scale of a sample, the presence of defects is influenced and determines the mechanical properties accordingly. [1] On side to these defects, there could be also problems related to deformations, usually caused by the uneven drying during the seasoning process or by a change in moisture content, and shrinkage, which indicates a partial drying. The contraction of wood always occurs in the previously-mentioned three directions. [16]

Finally, trees exhibit structural and chemical plasticity forming specific tissue types, like reaction wood, to deal with specific loading conditions or to control and change the growth direction of stems and branches. These tissues differ notably between softwoods and hardwoods in terms of structure, as well as in their biomechanical functionality, and are an additional source of structural diversity. [1]

I. b. 2. OPTICAL PROPERTIES

Wood appears naturally brownish in color in the visible spectrum (Fig. 8) due to the absorbance of light, mainly by lignin, attributed to the chromophoric structures and groups (benzene rings, quinonoid, vinyl, phenolic hydroxyl, and carbonyl groups), even if they vary between wood species. The chromophores are in fact a region in a molecule that absorbs energy in the visible spectrum, allowing the molecule to appear colored. [17] While lignin absorbs in the visible spectral range, cellulose and hemicellulose are optically transparent. [18]

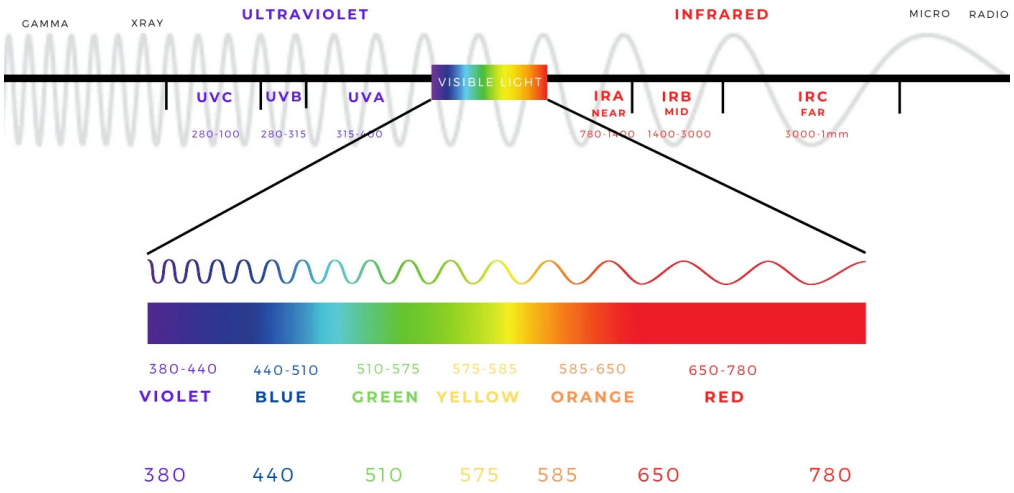

Figure 8. Visible spectrum. [19]

The pore structure at both microscale and nanoscale has a key role in determining the optical properties of the material because it creates multiple air-tissue interfaces that are unfavorable for photon transport, as well as wood's non-homogeneous chemical composition. [1] The amount of light absorption strongly depends on the chemical composition, while the amount of light scattering is related to the wood structure. Strong light scattering occurs at the boundaries between air-filled cellular void channels and the solid nanocomposite matter of the cell walls (i.e., cellulose, residual lignin, and hemicellulose) due to the refractive index mismatch between these components (= ca. 1.53 in average) and air (= 1). [4] The refractive index is a unitless number that gives indication of the light bending ability of a medium; in other words, the ratio between the speed of light in vacuum conditions and the one in a given material. A uniform pore distribution reduces light scattering and allows light to pass. [20] [21]

The anisotropic nature of wood creates another optical phenomenon called birefringence, or double refraction, in which light is split into two rays, each one traveling at different speeds and refracted at different angles. These two polarized rays are known respectively as ordinary and extraordinary. In other words, when light enters a birefringent material like wood, it behaves as if the material has two different refractive indices, depending on the direction of the light's polarization. Instead of bending in just one direction, it splits into two rays. [22] [23]

I. b. 3. THERMAL AND ACOUSTIC PROPERTIES

The ability of a material to conduct or transfer heat or sound is referred to as thermal or acoustic conductivity, respectively. In wood, it depends on factors such as density, presence of defects, moisture content, direction of the flow, as well as the kind, quantity, and distribution of extractives such as gums, tannins, or oils. [1] [9]

Wood naturally demonstrates low thermal and acoustic conductivity and anisotropic transport due to its porosity, low levels of crystalline bio-polymeric components, and structural anisotropy at multiple scale. However, wood that is soaked with a large amount of water has a higher thermal and acoustic conductivity than dry wood. In fact, the thermal conductivity of wood, ranging from 0.1 to 0.2 W/mK under dry conditions, increases with moisture content due to the higher conductivity of water compared to air. [24] [25] Therefore, the moisture content must be considered in the measurement of thermal properties and the thermally-related use of wood. For what concerns acoustics, instead, wood's cellular structure makes it an effective sound absorber and vibration dampener, especially at mid-to-high frequencies. This intrinsic damping behaviour arises from the internal friction among the cell walls polymers and viscous drag of air within the pores. [26] [27]

Another factor that influences the thermal and acoustic properties of wood is the pore structure and, particularly, the nanopores with a size smaller than that to allow a free path of phonons in air. Phonon transport in these confined spaces is inhibited, leading to improved insulation. Furthermore, the presence of many pores introduces numerous air-tissue interfaces, which may disturb the phonon transport. [1]

Finally, the three main components of wood present different conductivities: by tuning the crystalline structure and/or orientation of the cellulose fibrils, although challenging, should be effective in obtaining the desired thermal and acoustic properties. [1]

I. b. 4. FIRE RESISTANCE

Wood exhibits a characteristic behaviour under fire exposure. Being a porous material with low thermal conductivity, as previously mentioned, heat penetration occurs slowly, allowing the unexposed core to remain relatively cold. When subjected to high temperatures, wood undergoes the

pyrolysis process, which leads to the formation of a protective surface char layer (Fig. 9). This has a significantly lower thermal conductivity than the unexposed wood, effectively insulating the core, reducing oxygen diffusion, and slowing down further degradation. [28] As a result, timber members maintain their structural integrity for extended periods during a fire, despite the progressive reduction of their cross-sectional area.

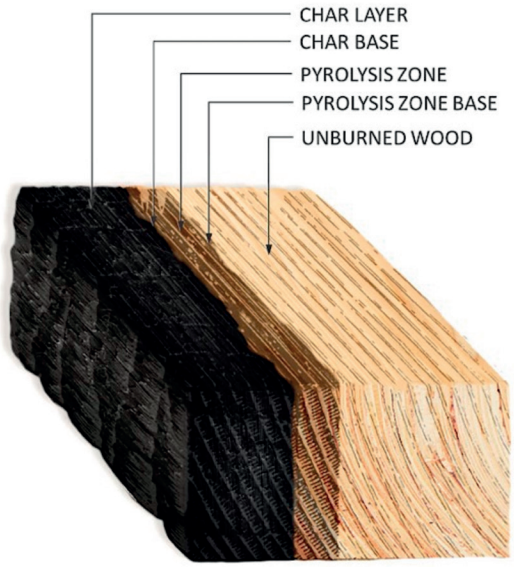

Figure 9. Degradation zones in a section of burnt wood. [28]

The fire resistance of wood depends on several factors, including moisture content, density, geometry, and exposure conditions. [29] Higher moisture content can delay ignition because the absorbed water must evaporate before pyrolysis occurs. Building Eurocode 5 typically account for wood's charring rate estimated between 0.6–0.8 mm/min for softwoods when designing fire-safe structures. [30] Thus, while inherently combustible, wood's predictable degradation makes it possible to engineer safe, resilient, and code-compliant timber structures.

I. b. 5. DIMENSIONAL STABILITY

The wood internal organization is intrinsically designed for the transport of water and nutrients from the tree roots to the upper trunk, branches and leaves through open channels defined by vessels and tracheids. [1] [9] The hierarchically-aligned porous structure of wood and the hydrophilic nature of cellulose and hemicellulose are crucial for water transport, allowing passive capillary force to move water upwards along the stem axis. [1]

Water exists in wood in three forms: bound water, free water, and vapor. The first one is chemically bonded within the cell wall matrix, the second is located in the cell lumina and intercellular spaces, while the latter resides in pore spaces in equilibrium with the ambient humidity. The Equilibrium Moisture Content (EMC) of wood is a function of relative humidity and temperature; fluctuations in EMC lead to swelling or shrinking, a phenomenon known as dimensional instability (Fig. 10). [23] [24] Given this hydrophilic nature of cellulose and the polarity of water molecules, water plays a role in the bonding between cellulose chains. Water molecules increase the distance between neighbouring cellulose fibrils but also facilitate the formation of bonds between cellulose chains via water, thus creating cellulose-water-cellulose hydrogen bonds. Even though the single hydrogen bond between cellulose and water is weaker than a direct cellulose-cellulose bond, water enables so many of these bridges that the total bonding strength increases dramatically. [7] When water molecules are introduced at the interface of the cellulose fibrils, the Young's modulus of the cellulose hierarchical structure

remains nearly constant, despite changes in interfacial water content. This because the structure is still in the initial linear elastic phase, where interlayer sliding occurs without significantly affecting stiffness. However, the fracture energy and peak stress increase significantly with increase in the water content, but the strengthening and toughening are limited by a reasonable range. When the water content is larger than 3.75 $H2O/nm^2$, water molecules start creating hydrogen bonds between them, which results in diluting the interfacial bonding strength and a lower fracture energy. [7]

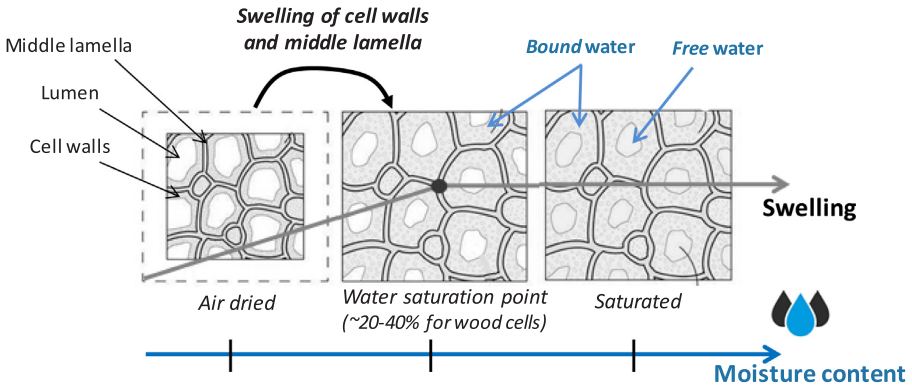

Figure 10. Swelling and water state according to moisture content in wood cells.
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The hydration state of the cell walls and lumens is of fundamental importance to the mechanical properties of wood, particularly when variations of moisture content occur as a consequence of changes in the environmental conditions (e.g., relative humidity and temperature). Such variation of moisture content in wood can influence the macroscopic physical properties of wood, but water inside wood strictly affects also the birefringence intensity and light scattering, aside to influencing the thermal properties. [23]

I. b. 6. DURABILITY

Because of the organic composition, porous structure, and hygroscopic characteristics, wood may be attacked and undergo degradation, and its decay types are either abiotic or biotic. Abiotic decays are due to environmental conditions, like UV radiation, high temperatures, fire, or chemical agents. They are usually not of considerable importance because decay occurs on the surface only and progresses at minimal speed. Biotic decays, on the other side, are due to biological attacks and are difficult to remediate; therefore, they are the most worrying cause of deterioration. Curative treatments are available, like self-healing coatings, fumigants, gases, heating, and, if needed, removal. Preventive treatments, instead, may block potential future attacks through best practices, coatings, paints, ventilation, and monitoring activities. [32] [33]

When the environmental moisture content is above 20%, wood may be attacked by fungi, and so by moulds and insects. [32] The most widespread attacks are by two types of basidiomycetes, known as brown and white caries. The first demolishes cellulose, leaving lignin almost intact, while the second attacks both cellulose and lignin, crumbling the wood. [34] Monitoring humidity rates, providing ventilation, and using sacrificial elements when wood is exposed to outdoor conditions are considered preventive treatments. Curative treatments, instead, involves fumigants, which have environmental safety concerns, or the removal of damaged parts with substitution with prosthesis. [35] Moulds are a direct consequence of fungal attacks and provide no structural damage. Anti-mould treatments and subsequent brushing are enough to solve the issue. Finally, insects, which are xylophagous, are less serious than fungal decay, but are able to attack even the most seasoned wood and under 20% humidity level. The damage occurs by digging tunnels and rosume, that is wood dust and excrements; in most cases, it is more an aesthetic damage rather than a structural threat. [32]

The susceptibility of wood to decay is closely linked to the tree species. Some tropical or resinous trees have a natural decay resistance due to the presence of phenolic compounds, tannins, or oils. Species that are naturally resistant to decay-causing fungi include redwood, cedar, bald cypress, black locus, and black walnut, while the insect-resistant species include redwood, eastern red cedar, and bald cypress. Many commercial woods instead, particularly softwoods, are vulnerable and require treatment for outdoor applications. [36] [37]

From a functional point of view, the hygroscopicity of wood is both a liability and an opportunity. In structural applications, the dimensional changes due to humidity cycling can lead to splits and cracking, particularly in untreated or poorly-laminated wood products. [32] However, controlling the moisture sensitivity has the potential in moisture-driven shapes for a passive climate-responsive architecture. The future of wood-based material science lies in convergent technologies: the programmable degradation of wood components under specific environmental triggers would complete a designed ecological lifecycle without waste. [38]

I. c. ENGINEERED WOOD

Although wood is widely recognized in the context of structural timber products such as Cross-Laminated Timber (CLT) and Laminated Veneer Lumber (LVL), this section focuses on a different and increasingly important dimension of engineered wood: nanoscale modification and functionalization. Recent years have seen a new interest in wood, not merely as a raw material but as a starting point for Engineered Wood Products (EWPs) and bio-inspired materials. They represent the effort in enhancing or repurposing wood's natural properties through either physical and chemical processes, or a combination of these two. [1] [7]

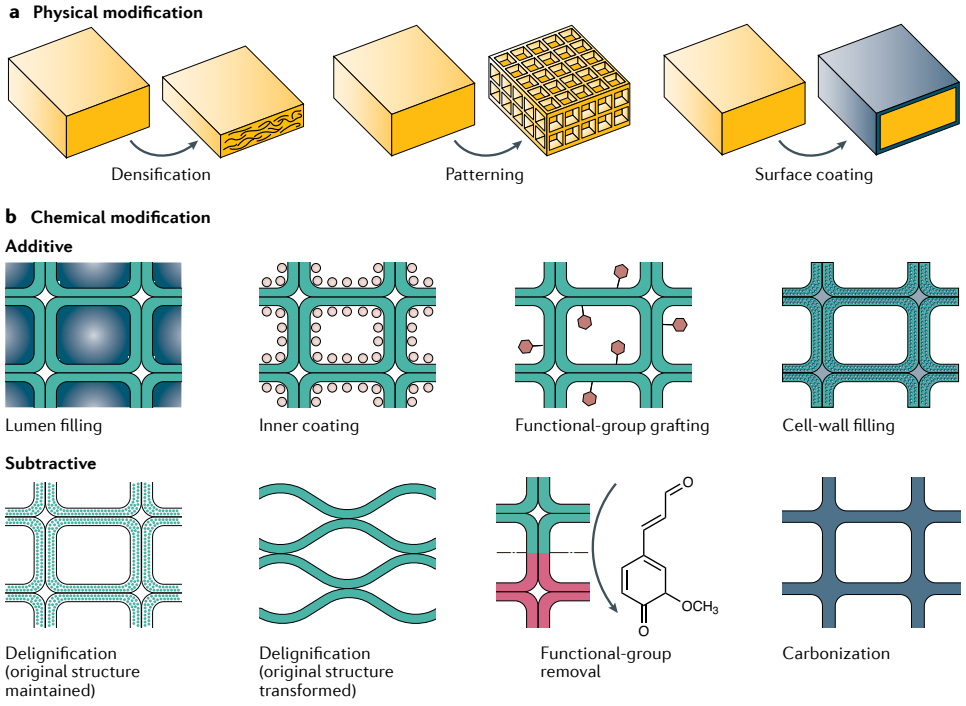
Wood modification aims at overcoming one or more disadvantages and weaknesses of natural wood by altering its physical and chemical structures and properties, substantially improving them according to the desired function. To do so, the hierarchical structure of wood is highly beneficial for the modification and functionalization of the wood scaffold due to the multiple accessible levels for interventions, and especially at the cell-wall level due to the abundant reactive groups, such as hydroxyls, and highly ordered network of fibrils. At the same time, the similarities of the cell-wall structures among the different wood species allow the application of similar modification protocols. [1] [7] Early modification strategies focused on improving stability rather than adding functionalities. [1] Although the overall performance was improved, the control of such modifications was imprecise, owing to the limitations in material synthesis and characterization techniques. Recent developments in nanotechnology have enabled instead the addition of properties and functions to wood-based materials from the macro to the molecular scale. [1] Among these, physical approaches like wood surface modification can improve the binding strength, optical properties, stability, hydrophobicity, reactivity, and other intrinsic properties of wood, while chemical modification of wood includes, but is not limited to, selectively removing components, such as lignin, changing their chemical structures, or introducing new functional groups.

Intervening on the cell walls is crucial for optimizing the properties of wood. For example, filling the open cells with an in situ polymerization produces a transparent wood composite, whose result combines the properties of both the wood and the polymer, leading to improved mechanical strength, optical clarity, and thermal insulation. [7] The interface between the original and added materials has a distinctive role in altering the properties and functions of modified wood. [1] This new innovative material is at the core of this thesis because, with its improved characteristics, has gained the potential of substituting traditional materials like glass and transitioning to a new bio-based and sustainable future, all themes that will be discussed in the next chapters.

On the other side, by reducing the pores and voids size between cell walls, the densification of wood is an efficient approach to optimize the mechanical strength of low-density wood. [7] Distinguished from conventional densification methods, the pre-treatment of partial delignification, which consists of partially removing lignin and hemicellulose, makes it possible to fully densify the natural wood structure with an approximately 80% reduction in thickness. [7] In fact, there is a softening of the lignin-hemicellulose matrix that facilitates the collapse of lumens, ultimately reducing the resistance of the wood scaffold to compression. The porous wood structure contains lumens along the wood growth direction, while the resulting densified wood is mainly composed of fully collapsed wood cell walls, which are closely intertwined and densely packed. This microstructure enhances the hydrogen bonding between neighbouring nanofibers, while residual lignin plays a key role as a binder, enhancing the mechanical performance. [7] Furthermore, this method also drastically reduces the quantity and size of the pore defects, leading to a much higher strength than natural wood. [7]

Chemical modifications are then conducted almost exclusively via the reactions of hydroxyl groups of cellulose, hemicellulose, and lignin. An example is the cross-linking method, which creates bridge linkages between molecules of cellulose, hemicellulose, and lignin, via the reactions between hydroxyl groups and cross-linking reagents, such as epoxy resin and isocyanate. [7] Recent experimental research successfully obtained strong and tough wood by a three-step delignification process, drying-induced assembly, and water molecules-induced hydrogen bonding under compression. The resulting composite had a densified structure with improved mechanical properties (2.4 times increase in tensile strength, 2.7 times increase in Young's modulus, and 1.4 times increase in density) with respect to natural wood. [7]

Overall, inspiring from the different approaches, a selection of modification strategies may be identified (Fig. 10). Among the physical approaches (a), the densification is the most common one, followed by patterning and surface coating. Chemical modifications (b), instead, present a wide variety of subtractive approaches that include the delignification, with the original structure maintained or transformed, carbonization, and removal of functional groups, but also additive methods with lumen or cell-wall filling, inner coating, and functional groups grafting. Delignification may also be the base for a combined modification (c), coupled with densification, filling, or grafting, while carbonization with coating techniques. [1]



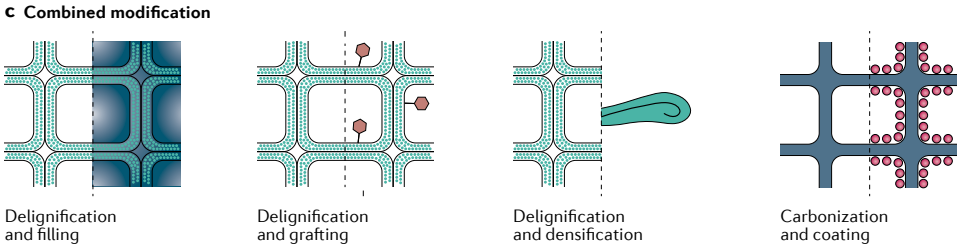


Figure 11. A selection of modification strategies. Reproduced from [1] under the licence ID 1673421-1.

The porosity of natural wood gives opportunities for additional functionalities, thus extending the application range beyond the traditional use of wood materials and enabling the development of new advanced materials that can integrate optical, mechanical, thermal, and other properties together. This expanded functionality positions engineered wood as a versatile platform for the next-generation sustainable materials.

II. TRANSPARENT WOOD AS A NEW MATERIAL

Transparent wood is an emerging material that combines added optical transparency, mechanical strength, and thermal management properties. It was first reported by Siegfried Fink in 1992 in his article "*Transparent Wood - A New approach in the Functional Study of Wood Structure*" while trying to facilitate wood anatomy studies. [39] This is recognized as the first paper that describes the preparation processes. However, the author's purpose was to observe the 3D internal structure of wood rather than creating a new material. The study of transparent wood thus began when the scientific community understood the enormous potential of this bio-composite and was later rediscovered by the University of Maryland and KTH Royal Institute of Technology, separately, in 2016. [40]

Transparent wood-based materials can be prepared through either bottom-up or top-down approaches. Bottom-up strategies rely on nanocellulose building blocks to construct thin films or bulk transparent structures. These methods are resource-intensive, requiring large amounts of chemicals, energy, and water, which pose challenges for sustainability. On the contrary, top-down approaches directly transform natural wood into transparent structures by selectively removing or modifying its components while preserving the anisotropic cell wall composition. This method not only enhances the mechanical properties by retaining highly-oriented cellulose fibrils but also avoids resource- and energy-intensive processes inherent to bottom-up methods. [41] The structural combination of the different sizes of pores in wood leads to much light scattering because of the mismatched refractive indices at the boundaries between the air-filled lumen spaces and cell walls. [41] To obtain transparent wood materials, therefore, two main steps are necessary: (i) removing or modifying the light-absorbing components and (ii) eliminating the light scattering in the bleached scaffold by impregnating it with refractive index-matched polymers.

Two strategies are acknowledged to remove the natural color of wood and increase its whiteness: either by removing lignin (delignification) or decoloring wood (bleaching). In the lignin-removing strategy, the aim is to obtain a porous scaffold to increase light transmittance and facilitate polymer impregnation. This may be achieved through the use of strong chemicals such as chlorine-based agents and oxidants to destruct and dissolve lignin, or by employing lignin-degrading enzymes. The bleaching method, instead, employs milder reductive or oxidative treatments to selectively decolour lignin by altering or removing its chromophoric groups while preserving most of the macrostructure. In both cases, polymer impregnation adapts within the wood scaffold. [40] [41]

The growing demand for sustainable and renewable materials in the construction sector has positioned EWPs as a key component of environmentally-responsible building strategies. [7] Within this context, transparent wood represents an innovative material with the potential to redefine architectural applications. It uniquely integrates mechanical robustness with optical transparency, enabling, among others, applications in modern green construction and smart building design. [2] Furthermore, its properties allow for light transmission with uniform distribution, maintaining privacy and contributing to indoor environmental quality. [4]

II. a. PREPARATION PROCESSES

During the preparation of transparent wood, it is crucial to precisely control wood's nanopores in the cell walls through appropriate treatments and process conditions (e.g., treatment time, concentration of chemical solutions, pH value, and temperature). [41] One of the primary obstacles of the preparation lies in the low permeability of the dense wood cell wall, which restricts access for chemical treatments and functionalization. To overcome this, it is necessary to partially and selectively remove certain components of the wood, among which lignin plays the most critical role. [2]

Lignin is a complex aromatic polymer embedded in the cell wall and responsible for the brownish colour of wood; it contains chromophores that absorb and scatter light, making the material opaque. [41] For this reason, the preparation of transparent wood largely depends on the removal or modification of lignin. Delignification is the preferred method to facilitate the removal of light-absorbing chromophores while simultaneously generating nanoscale porosity in the cell wall, which is useful for further functionalization. In contrast, the lignin-retaining method is advantageous to provide wood substrates with higher mechanical strength. [2] Both approaches are then followed by impregnation with a compatible polymer, the fundamental step to impart the characteristic optical clarity of transparent wood.

II. a. 1. DELIGNIFICATION

Delignification can be defined as the process of removing lignin from natural wood via chemical treatment (Fig. 12). [1] This results in the reduction of light absorption and scattering, generating a whitish wood scaffold that is later ready to be impregnated with polymers to achieve the characteristic optical transparency.

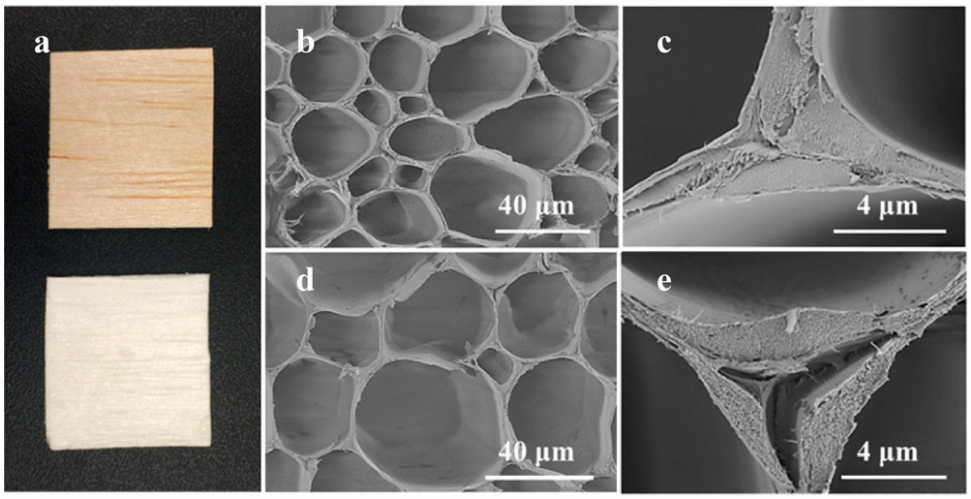


Figure 12. Comparison in appearance between natural wood and bleached wood (a).
Delignification process through SEM images showing lignin removal (d) (e) with respect no natural balsa wood (b) (c). [42]

Chemical delignification is the most widely applied approach, and it can be classified into alkali, sulphites, and solvent-based processes, depending on the types of chemicals used. [7] [43] In alkaline systems, bases like sodium hydroxide (NaOH) are used to depolymerize lignin. However, when applied alone in the so-called soda pulping, they are often insufficient, especially for softwoods, because hydroxide ions (OH-) are weak, making the reaction slower and lacking extensive depolymerization of lignin. To improve efficiency, sodium sulphide (Na_2S) is added in kraft pulping. [7] Oxygen is a sulphur-free alternative for soda pulping, but because this system is unselective it may also attack cellulose, compromising the overall structural integrity of wood with the formation of micron-sized holes in the cell wall. [7] Sulphite processes, on the other hand, rely on lignin sulfonation, where wood is treated with sulphur-based reagents that improve lignin solubility across a wide pH range. [7] Finally, in solvent-based processes lignin is depolymerized and then dissolved in a solvent, like organic solvents (ethanol, methanol, acetone, formic acid, acetic acid, etc.) or more advanced media like ionic liquids, Deep Eutectic Solvents (DES), and acid hydrotropes. [7]

Two chemical methods have become standard in laboratory research. The first uses acidified sodium chlorite ($NaClO_2$) in an acetate buffer solution, with pH 4.6 for 6-18 hours, typically at 80 °C, depending on the size and cutting direction of the sample. The reaction is stopped when the wood sample becomes white. This process removes lignin selectively from the middle lamella, where is mostly

concentrated, while preserving the natural honeycomb-like cellulose framework; for these reasons, it is widely used for softwoods. [2] [43] A study using sodium hypochlorite (NaClO) was reported by Fink himself in 1992, which resulted in the dissolution of lignin in water due to oxidation and chlorination reactions. [39] The second, instead, employs an aqueous solution of Peracetic Acid (PAA), which is chlorine-free and therefore more environmentally sustainable and particularly attractive in the context of green chemistry. Produced from acetic acid (CH_3CO_2H) and hydrogen peroxide (H_2O_2), PAA ($C_2H_4O_3$) can delignify wood under moderate conditions, with pH 4.8 for 24-48 hours, typically at 25 °C. The reaction is stopped when the wood sample becomes white. [9] These two standard methods are summarized and compared in the following table:

	Acidified Sodium Chlorite	Peracetic Acid (PAA)
Chemical composition	*$NaClO_2$ in acetate buffer solution*	*$C_2H_4O_3$ produced from acetic acid (CH_3CO_2H) and hydrogen peroxide (H_2O_2)*
Reaction temperature	*60-80 °C*	*ca. 25 °C (room temperature)*
Reaction time	*6-18 hours*	*24-48 hours*
pH	*4.6*	*4.8*
Lignin removal selectivity	*Selectively removes lignin from middle lamella, preserving cellulose framework*	*Uniform delignification*
Resulting wood appearance	*Whitish, preserves honeycomb-like cellulose structure*	*Whitish, retains structural integrity*
Wood type suitability	*Particularly effective for softwoods (high lignin content in middle lamella)*	*Suitable for both hardwoods and softwoods*
Environmental impact	*Less environmentally friendly for the use of chlorine-based reagents*	*Green chemistry method (chlorine-free)*
Byproducts	*Chlorine dioxide (ClO_2) gases*	*Acetic acid and water (benign)*
Subsequent treatments	*Often followed by bleaching (e.g., H_2O_2, $NaOH + Na_2SO_3$)*	*Can be combined with hydrogen peroxide (H_2O_2) bleaching for optical clarity*
Advantages	*Fast reaction, preserves the structure, strong selectivity*	*Environmentally friendly, mild conditions, versatile*
Limitations	*Chlorine-based reaction, with related safety and environmental issues*	*Slower reaction, possible low control over lignin removal*

Table 3. Comparison between two standard chemical methods for delignification process.

Hydrogen peroxide (H_2O_2) is also widely applied either alone or in combination with alkaline treatments to further remove chromophores after partial lignin removal. It is typically used at high concentrations and under elevated temperatures, sometimes even through steam-assisted activation, to effectively break down and dissolve lignin. [7] [44] For example, Zhu et al. (2016) utilized a solution combining sodium hydroxide (NaOH) and sodium sulphite (Na_2SO_3) to boil wood samples for 12 hours, effectively removing lignin. Subsequently, they bleached the material with hydrogen peroxide (H_2O_2) and impregnated the scaffold with epoxy resin under vacuum conditions, producing transparent wood with high optical clarity. [45]

While effective, chemical methods have significant drawbacks. They often require long treatment times, consume large amounts of reagents, and can generate byproducts that are toxic or environmentally harmful. In addition, excessive delignification may weaken the wood, removing up to 30% of its weight and significantly reducing the mechanical strength, thus challenging the handling and preparation of large samples. [7] For example, even if chlorite is an effective delignification reagent to selectively destruct lignin without affecting cellulose and hemicellulose, its costs and environmental concerns, like the continuous handling of hazardous gases, make it unfeasible for large-scale productions other than that of a laboratory. [7] To address these limitations, researchers have explored enzymatic delignification as a more sustainable way. Enzymes such as laccase, a copper-containing oxidase, can break down lignin by oxidizing phenolic groups of the lignin polymeric structure

and converting them into lignin decomposers. [44] The efficiency of enzymatic treatments can be also improved by setting the proper temperature and pH or by adding hydrogen peroxide (H_2O_2). This approach not only maintains the layered structure of the wood tissue more than harsh chemical treatments, but also effectively reduces pollutants and supports recyclability. On the other side, the cost of using biological enzymes is much higher than that of chemical reagents as it requires sterile conditions and precise environmental control during the experiment. [44]

A key aspect of delignification is achieving an optimal balance between transparency and mechanical strength. While full removal of lignin maximizes light transmission, it also weakens the wood scaffold; retaining part of the lignin, instead, preserves strength but reduces transparency. This opens a debate on whether delignification is necessary for transparent wood preparation and opens the door to bleaching techniques. [9]

II. a. 2. LIGNIN MODIFICATION

Following what was just mentioned, the lignin-modification strategy has developed as a viable alternative to lignin removal, which often leads to substantially lower bulk structural properties, since lignin functions as a natural binder within the wood matrix. This method does not extract lignin but rather alter its structure by eliminating the chromophoric groups and expands the range of wood species that can be utilized. [40] [41] In fact, species with high lignin content may be difficult to delignify without compromising the structure, while species with low lignin content may lose the overall structural integrity after removal. This approach, instead, being also less invasive, offers the potential to prepare transparent wood on a larger scale, thus addressing not only performance issues but also the related scalability challenges. However, excessive lignin retention may compromise the optical performance by lowering transmittance and increasing haze values, which limits the efficiency of the composite. [7]

The process for preparing a transparent wood composite with the lignin modification strategy involves the samples to be immersed in an alkaline bleaching solution, becoming visibly whitish, and then into polymer for infiltration, thus resulting in a transparent sample with maintained structure (Fig. 13).

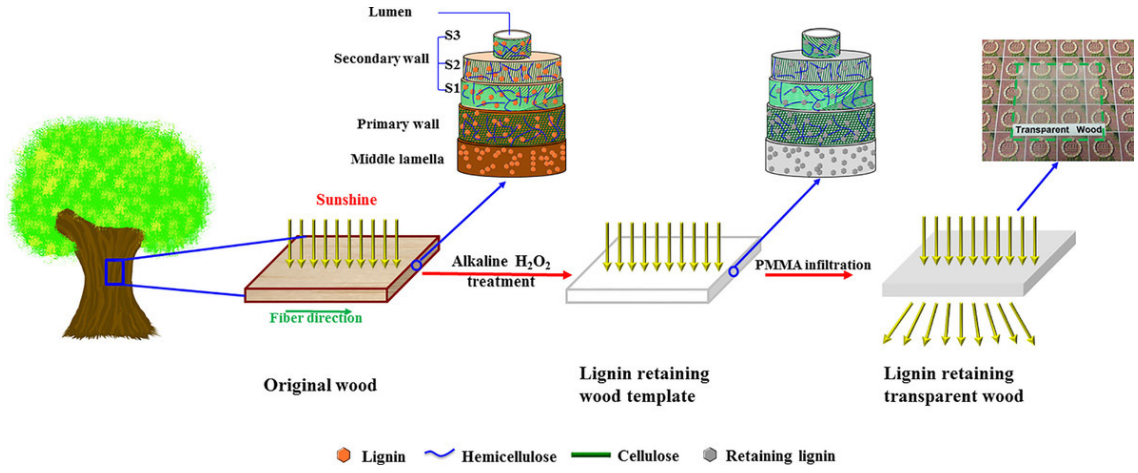


Figure 13. Schematic diagram of the preparation of lignin-retaining transparent wood. [43]

During the bleaching process with hydrogen peroxide, the H_2O_2 molecule decomposes to form hydroxyl radicals. These are highly reactive and target the double bonds and chromophoric groups in lignin. In doing so, they disrupt the delocalized electron systems and take electrons or oxygen atoms from the aromatic rings and side chains. The result is chromophoric groups turned into colorless compounds and the selective oxidation of lignin while at the same time largely preserving cellulose and hemicellulose. [47]

In a notable study, Li et al. (2017) used a bleaching solution (Na_2SO_3/NaOH/H_2O_2) showing that more than 80% of the lignin content was retained. As a consequence, the wood cell wall did not present substantial micro- and nano-scale pores, resulting in a better-preserved wood structure and favourable mechanical properties under wet conditions. [43] Similarly, treating wood with hydrogen peroxide (H_2O_2) at a temperature of 70 °C effectively removes the pigment groups; compared to untreated wood, it has no evident change in the structure nor gaps in the cell wall. [44] Xia et al. (2021), instead, demonstrated such a method by brushing hydrogen peroxide onto the wood surface and subsequently exposing the template to UV radiation. [46] If on one side this other technique is efficient in modifying lignin, on the other it requires a long and slow process.

II. a. 3. POLYMERIZATION

After delignification or bleaching, wood typically turns pale or whitish, remaining opaque; this is because light continues to scatter at the interfaces between air, cellulose and hemicellulose inside the porous scaffold. In natural wood, light scattering already occurs due to the intrinsic hierarchical porosity of the cell walls and lumina, where air and solid phases coexist. [4] During delignification, however, the removal of lignin enlarges the lumens or creates additional voids within the structure. While this increased porosity is beneficial for subsequent polymer infiltration, the presence of air pockets, either already existing or newly accentuated by lignin removal, further prevents transparency. [1] To achieve optical clarity, these voids must be filled with polymers that match the refractive index of the wood. Polymer impregnation, therefore, represents a fundamental step in the preparation of transparent wood.

The optical opacity of wood can be explained by the Snell's law, also known as the law of refraction, that describes how light is scattered passing through an interface between one medium and another that have two different refractive indices. This is expressed by the formula $n_1 (\sin \theta_1) = n_2 (\sin \theta_2)$ where *n1* and *n2* are the refractive indices of the two materials and θ_1 and θ_2 the refractive angles of incidence and refraction, respectively. When the refraction angle is high, and so the mismatch is large such as between cellulose (refractive index ≈ 1.53) and air (refractive index ≈ 1.0), significant scattering occurs, resulting in opacity. By replacing air with a polymer that has a similar refractive index to cellulose, this mismatch is minimized, thus reducing haze and increasing transmittance (Fig. 14). The result is a composite material where the polymer acts as both an optical filler and a mechanical binder, and the wood scaffold provides the structure. [42] [48]

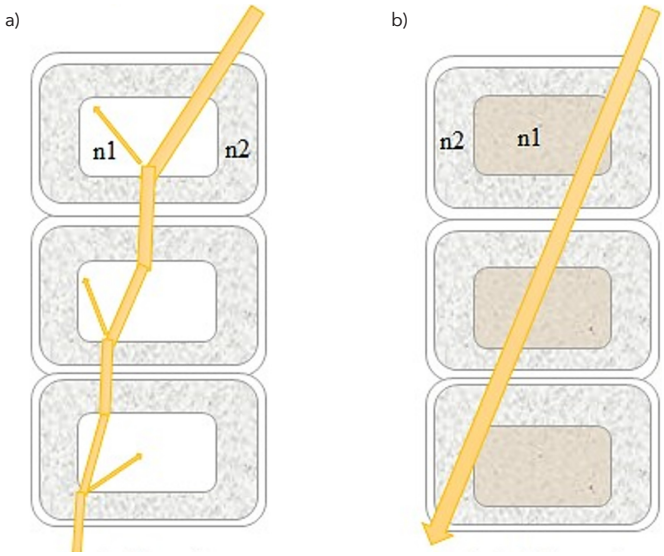


Figure 14. Pathway of a light ray through wood cells filled with air (a) and a material of the same refraction index (b). Reproduced from [9] under the licence ID 1678291-1.

A long-chain molecule of one or more repeating units of atoms, linked together by strong covalent bonds, is known as polymer. [49] Polymers are broadly divided into thermoplastics and thermosets. Thermoplastic polymers, such as Poly-Methyl Methacrylate (PMMA), soften when heated and can be reshaped reversibly, while thermoset polymers, such as epoxy resins, undergo chemical cross-linking during the curing phase, which makes them mechanically strong but irreversible in shape once set due to the chemical bonds. PMMA is one of the most common polymers used for preparing transparent wood. Known with its commercial names of Plexiglas, Perspex, or Lucite, PMMA is valued for its high transparency, resistance to yellowing and UV degradation, and ease of processing at relatively low temperatures. It is often used as a lightweight, shatter-resistant alternative to glass. [12] On the contrary, epoxy resins cure at a slower rate but form stronger and more durable bonds, which make them suitable for structural and load-bearing applications. They are made by a resin and a curing agent that form a densely cross-linked network; however, due to their high viscosity before curing, impregnation must be assisted by vacuum to achieve uniform polymer distribution. [9]

All the different characteristics of PMMA and epoxy resin, representing thermoplastic and thermoset polymers, respectively, may be summarized in the following table:

	Poly-Methyl Methacrylate (PMMA)	Epoxy resin
Polymer type	*Thermoplastic*	*Thermoset*
Chemical structure	*Linear polymer chain of Methyl Methacrylate (MMA) monomers*	*Cross-linked network formed by the reaction of epoxy resin with curing agent*
Viscosity	*Low, allows deep infiltration into micro- and nanopores*	*High, requires vacuum or pressure-assisted impregnation*
Refractive index	*1.49*	*1.50-1.55 (tuneable via curing agent)*
Impregnation process	*Infiltrated as a pre-polymer*	*Infiltrated as low-viscosity resin and cured inside wood*
Curing	*Free-radical polymerization of MMA*	*Chemical cross-linking between resin and curing agent*
Infiltration behaviour	*Excellent infiltration due to low viscosity*	*Requires vacuum to ensure full impregnation*
Bonding with wood	*Physical adhesion, low chemical interaction*	*Strong chemical bonding with hydroxyl groups of residual cellulose and lignin*
Optical properties	*High transmittance*	*Moderate to high transmittance*
Mechanical properties	*Moderate stiffness and strength, brittle under impact*	*High strength, toughness, and dimensional stability*
Applications	*Decorative panels, solar devices*	*Structures and functional composites*

Table 4. Comparison between thermoplastic and thermoset polymers for impregnation.

Different polymers require specific processing conditions also before the impregnation phase. For example, Methyl Methacrylate (MMA) is pre-polymerized with a reactive agent at 75 °C for 10-15 minutes per each mm of thickness. The reaction is stopped at about 20% of conversion by rapidly cooling it down with ice, obtaining a partially polymerized MMA solution. The aim is to obtain an optimal viscosity to facilitate the following impregnation. This pre-polymer is then infiltrated into the wood scaffold under cool conditions, while full polymerization occurs in situ (inside wood) at 75 °C for 4-5 hours, yielding a stable PMMA composite. [2] [12]

The impregnation process then requires careful consideration. First, as mentioned before, the polymer must match the refractive index of cellulose to minimize interfacial scattering. Second, strong adhesion between polymer chains and cellulose microfibrils is necessary to ensure mechanical integrity. For this reason, some polymers are functionalized with hydroxyl (–OH) or carboxyl (–COOH) groups to form stronger bonds with the natural hydroxyl-rich wood surface. [4] Third, infiltration must be complete, fully filling the pores of the scaffold. This is often achieved using low-viscosity liquid polymers combined with vacuum-assisted impregnation. Such techniques are particularly useful for

dense hardwoods like birch or poplar, where the smaller pores and lower permeability complicate the impregnation; in softwoods like spruce and pine, instead, the larger pores allow an easier infiltration but may also increase light scattering. [9] [50] Finally, the polymer must provide dimensional stability. Since wood is naturally hygroscopic, polymers with hydrophobic characteristics are preferred to prevent water uptake, swelling, or warping. Additionally, matching the thermal expansion coefficient of the polymer with that of the wood is essential to prevent cracks or delamination under temperature variations. [24] The physiochemical characteristics of the impregnating polymer therefore have a great influence on the resulting mechanical and optical properties of transparent wood.

Towards a greener transparent wood, bio-based polymers have gained increasing attention. One of them is the Poly-Limonene Acrylate (PLIMA) monomer, synthesized by ring-opening acrylation of limonene oxide with acrylic acid. Wood is impregnated under vacuum conditions for 2-6 hours with LIMA containing a reactive agent as initiator. The impregnated samples are then placed between two glass slides, packed in aluminium foil, and polymerized at 75 °C for 24 hours, producing a bio-based composite. [2] LIMA undergoes free radical polymerization, which can proceed even in the presence of residual moisture, making it suitable for in situ polymerization within the wood substrates. The resulting Poly-Limonene Acrylate (PLIMA) thermoset shows a high glass transition temperature (Tg) of 131 °C, excellent optical transmittance (95%), and very low haze (≈ 3%). [2] These properties make PLIMA comparable to the commonly used petroleum-based PMMA while being derived from renewable resources. [2] Another noteworthy bio-based composite is chitosan, a natural polysaccharide obtained by deacetylating chitin, that is the main structural component of the shells of crustaceans, as well as of insect exoskeletons and fungal cell walls. Chitosan-based composites are typically prepared by dissolving chitosan in a mild acidic aqueous solution, where the polymer is rendered soluble. The wood scaffold can then be impregnated under vacuum conditions for an hour, after which the samples are oven-dried at 40 °C for two days. The resulting transparent wood composite presents less transmittance (80%) but a greater haze (30-60%). [52]

The selection of polymers that can be used for impregnation can therefore be summarized and compared in their main characteristics in the following table:

	Polymer type	*(n)*	Viscosity	Curing phase	Wood bonding	Optical properties	Mechanical properties	Ref.
PMMA (Poly-Methyl Methacrylate)	*Thermoplastic*	*≈1.49*	*Low – excellent impregnation*	*Free-radical polymerization; pre-polymerized MMA impregnated and cured at 75 °C*	*Mainly physical adhesion*	*High transmittance, low haze*	*Moderate stiffness, brittle on impact*	[2] [9] [12] [41]
Epoxy resin	*Thermoset*	*≈1.50*	*High – requires vacuum-assisted impregnation*	*Chemical cross-linking between two components (resin and hardener)*	*Strong chemical bonding (reactive OH groups)*	*Moderate-high transmittance, variable haze*	*High strength, toughness and dimensional stability*	[16] [53]
PLIMA (Poly-Limonene Acrylate)	*Bio-based thermoset*	*≈1.52*	*Medium-low*	*Free-radical polymerization at 75 °C*	*Good bonding with cellulose*	*High transmittance, very low haze*	*Good stiffness*	[2]
Chitosan	*Thermoset-like film former*	*1.53-1.54*	*Low*	*Physical film formation upon drying*	*Hydrogen bonding with cellulose*	*Medium transmittance, high haze*	*Moderate stiffness, brittle unless plasticized*	[35] [52]

Table 5. Comparison between different types of polymers for the preparation of transparent wood.

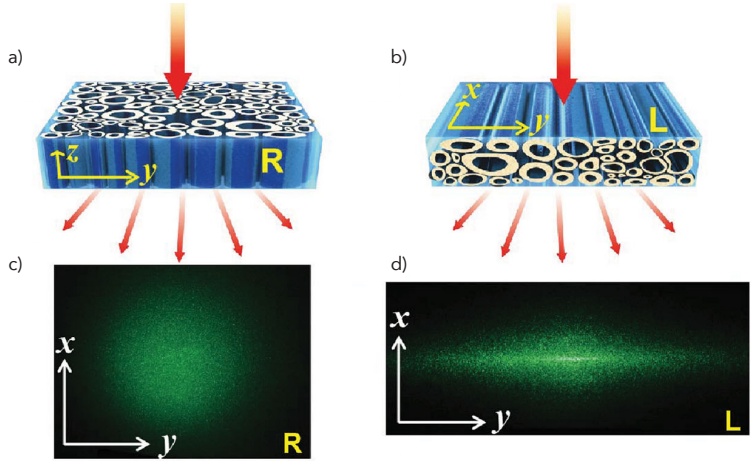
The vacuum condition is almost always adopted for an optimal polymer impregnation because it removes air trapped within the porous wood scaffold, allowing the liquid polymer to infiltrate deeply and uniformly into the voids. Without vacuum assistance, polymer impregnation relies only on diffusion and capillary forces, which is a much slower process that can take up to several days instead of few hours. Furthermore, it may risk an incomplete infiltration, thus leaving residual air pockets that lead to high optical haze, reduced light transmittance, weak interfacial bonding, and diminished performance. [42] [51]

Despite a careful refractive index matching, it is important to also note that residual scattering may still occur due to interfacial defects, such as polymer shrinkage during the curing phase or debond gaps caused by the incompatibility with the wood cell wall. Such issues may be mitigated by properly selecting thermoset polymers with low shrinkage strains to reduce the air gaps or by modifying the wood surface (e.g., esterification) to improve interfacial compatibility. [2] [41]

II. b. PROPERTIES OF TRANSPARENT WOOD

Transparent wood is a promising bio-based composite material whose properties arise from the synergistic contributions of the wood template and the impregnated polymer. The optical performance can be tailored through interfacial design between cell walls and polymers, which minimizes interfacial scattering and enhances light transmittance. Although the size and distribution of the pores intrinsic to the natural wood cannot be directly controlled, interfacial engineering and effective pore filling can mitigate scattering by reducing mismatches, while the alignment of cellulose fibers within the anisotropic wood structure can lead to polarization of light. By adjusting fiber orientation, transparent wood can achieve the desired direction-dependent optical effects, making it possible to tune light transmittance and haze according to the specific application needs. [2] [41]

The optical behaviour of transparent wood is therefore influenced by the anisotropic nature of wood (Fig. 15). When light travels parallel to the longitudinal direction of the wood fibers (R-wood), the polymer-filled lumens can guide it efficiently, reducing scattering. By contrast, in the transverse directions (L-wood), either radial or tangential, a weaker optical performance is observed due to the cell wall bending effects, although this can be mitigated by polymer impregnation that stabilizes the lumen space. [45] Overall, transparent wood exhibits tuneable transmittance (10–93%) and adjustable haze (10–98%), depending on factors such as wood species, thickness, cellulose volume fraction, and processing conditions. In particular, increasing wood thickness negatively impacts on the optical nature of transparent wood as light needs to travel longer pathways, leading to reduced optical transmittance. [16]



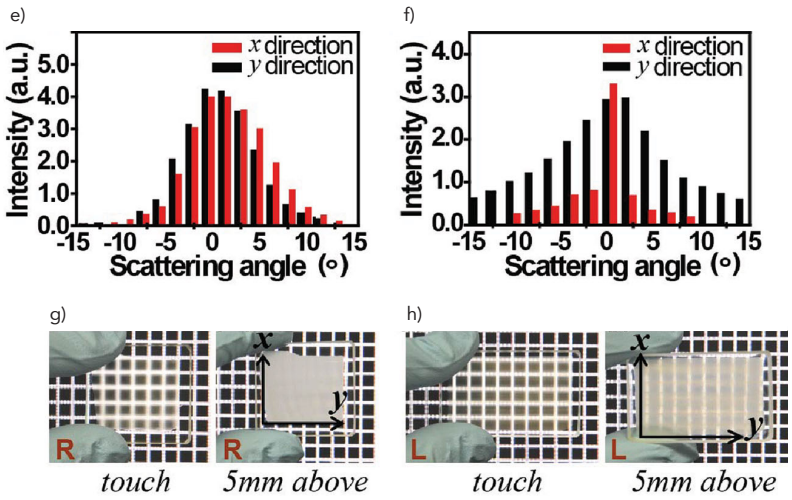


Figure 15. (a) (b) The transmittance measurement setup for transparent wood with two different anisotropic structures; (c) (d) The photo images of the scattered light spot for R-wood and L-wood, respectively; (e) (f) The intensity distribution in the x and y directions as shown in (c) and (d) for R-wood and L-wood, respectively; (g) (h) The R-wood behaviour; (i) (j) The L-wood behaviour.
Reproduced from [45] under the licence ID 1673940-1.

The degree of transparency is instead strongly influenced by the delignification or bleaching methods. For example, the sodium chlorite ($NaClO_2$) delignification can yield transparent wood with light transmittance up to 90% and haze as low as 10%, while the sodium sulphite (Na_2SO_3) method has demonstrated optical transparency above 85% but with haze values exceeding 95%. [41] [44] These variations highlight the critical role of chemical treatments, not only in the removal of chromophoric groups but also in preserving or altering the wood microstructure, which in turn affects the light scattering.

Beyond optical properties, transparent wood also demonstrates improved mechanical properties. The cellulose-rich scaffold provides high stiffness, while the impregnated polymer contributes to its toughness and fracture resistance. The complex hierarchical structure of wood, combined with composite effects, results in material toughening mechanisms that suppress crack propagation. Consequently, transparent wood is less brittle than glass and exhibits high flexural strength, dimensional stability, and improved impact resistance. [4] The weaknesses that arise in the transverse direction caused by anisotropy are largely offset by the polymer infiltration, which bonds to the cell walls and supports the overall structural integrity.

In summary, transparent wood represents a lightweight and high-performance biocomposite with a unique combination of optical transparency, tuneable haze, and improved mechanical strength. These properties, together with its bio-based origin and potential for broad applications, make it a promising alternative to traditional transparent materials such as glass and plastics for energy-efficient architecture, restoration interventions, indoor natural design, and solar technologies.

II. c. ASSESSING QUALITY OF TRANSPARENT WOOD

Assessing the quality of transparent wood as final product enhances the understanding of the process-structure-property relationships of wood. This collective information enables a more precise control and tuning of the wood composition, porosity, surface properties, fibril orientation, and molecular structure, all of which can accelerate the discovery of further modification and functionalization approaches.

As previously described, transparent wood exhibits two characteristic optical properties: transmittance, which measures the loss of energy transport through the material, and haze, which measures the loss of information, and so quantifies how much of the transmitted light is scattered. High haze reduces image clarity, lowering the ability to distinguish objects behind the material, while low haze enables a clearer vision. [4] Haze can be reduced by chemical treatments like acetylation to improve the compatibility at the wood-polymer interfaces, or by reducing the wood content. [4] Both haze and transmittance are strongly influenced by scattering phenomena occurring at the lumen-cell wall interface, Rayleigh scattering at the nanoscale within the cell wall, and the presence of air voids or other nanoscale defects acting as scattering centers. Not only, they both have different values depending on the orientation of the incident beam with respect to the wood fiber direction, based on the anisotropic nature of wood. [2]

To evaluate these properties, a range of analytical techniques is employed. Among these, the SEM (Scanning Electron Microscopy) provides detailed cross-sectional and surface morphologies of the wood scaffold, allowing observations of the cell walls, lumens, and microfibrils. [9] Through the SEM analysis, Cai et al. (2020) detected the morphologies of both natural and bleached wood, noticing that in the latter, after delignification, the cell lumen became larger compared to natural wood. [55]

FT-IR (Fourier Transform-Infrared spectroscopy) is used instead to analyse the chemical changes by detecting how functional groups such as hydroxyl (–OH), carboxyl (–COOH), carbonyl (C=O), and methyl ($–CH_3$), absorb infrared light at different wavelengths, thus providing the molecular fingerprint of cellulose, hemicellulose, and lignin. [9] The ATR (Attenuated Total Reflection) technique usually pairs with the FT-IR analysis for measurements directly on solid or liquid samples without further preparation. It consists of putting a crystal with a high refractive index, like a diamond, against the sample (Fig. 16). [9] The Infrared light beam enters the crystal (incoming IR beam) and reflects internally at the interface between the crystal and the sample (refracted IR beam), creating an evanescent wave that penetrates a few micrometres, typically 1-5 µm, into the sample. This is an electromagnetic wave that forms when light hits the interface between two materials and undergoes total internal reflection; it does not travel into the second material like a normal light wave, but it decays exponentially with distance. The detector then captures the resulting spectrum according to the characteristic IR wavelength at which the sample absorbed the energy.

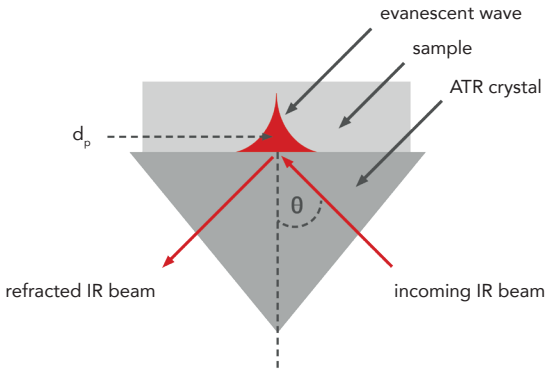


Figure 16. Evanescent wave resulting from total internal reflection. Adapted from [56].

Finally, XRD (X-Ray Diffraction) complements these techniques by investigating changes in the crystalline structure of the primary components present in wood (cellulose, hemicellulose, and lignin). With this technique, the details of the different structures can be mapped in 3D, enabling real time evaluations on polymer-wood compatibility by analysing the modifications after polymerization. [9]

In addition to its optical advantages, transparent wood retains high mechanical strength and toughness thanks to the hierarchical wood framework reinforced by polymers. It is therefore important to

understand how modification methods and preparation techniques impact the mechanical strength and other relevant properties. The mechanical performance is commonly evaluated through tensile and bending tests, which provide quantitative insights into strength, stiffness, and deformation behaviour under applied loads. [54] Tensile tests are carried out with a testing machine that elongates the specimen at a constant strain rate until failure, allowing the determination of tensile strength and Young's modulus. Bending tests, instead, consist on applying a load at one or two central points while the specimen is supported at both ends, allowing the assessment of flexural strength, modulus, and fracture behaviour. Achieving high wood volume fraction, low porosity, and strong interfacial adhesion between the wood matrix and polymer reinforcement in transparent wood is fundamental to obtain biocomposites with high axial strength and Young's modulus. [54]

II. d. FUNCTIONALIZATION OF TRANSPARENT WOOD

Through functionalization, transparent wood expands the range of application possibilities, while at the same time completely aligning with the design concepts of green comfort and aesthetics. However, the low permeability of the dense wood cell wall remains a major challenge for wood functionalization. [2] Improving cell wall accessibility is the key and this could happen through the partial and selective removal of wood components, among which there are the delignification and bleaching techniques. In the next paragraphs, some functionalization approaches are analysed to exploit the potential of this new material.

Hu et al. (2018) proposed an effective top-down approach to fabricate natural wood into the so-called nanowood, engineered at the nanoscale, where the delignification process not only removes thermally-conductive lignin components but also creates nanopores that impede phonon transport, resulting in largely reduced thermal conductivity. It also inherits the anisotropic structure form natural wood, giving rise to a thermal conductivity of 0.06 W/mK along the cellulose direction, while of a considerably lower value of 0.04 W/mK in the perpendicular direction. [57] In order to obtain samples of transparent wood with excellent insulation properties, a zinc oxide (ZnO) coating film with high emissivity (≈ 0.91) in the infrared (IR) wavelength can also be used. [44] A further approach is reducing transparency to near-infrared (NIR) radiation by impregnating delignified wood with a polymer matrix containing nanoparticles such as vanadium dioxide (VO_2), whose phase transition temperature, usually at 68 °C, can be lowered to room temperature by doping it with tungsten (W-VO_2). In this way, visible light transmission is partially allowed and IR reflected. [7]

Impregnation at the nanoscale was also adopted by Fu et al. (2021) to improve fire retardancy. Nano-clay particles are layered silicate minerals that, when dispersed in a polymer matrix, form a protective and thermally-stable barrier that slows down heat and oxygen diffusion into the wood. Alternatively, densified wood eliminates the space between cell walls to block the infiltration of oxygen and reduce transport of heat. Furthermore, a dense and insulating layer of wood char can be applied to further inhibit the diffusion. [58]

Molded wood has both compressive and tensile strengths higher than the natural wood, and comparable to some popular structural materials like aluminium alloys. [7] In the preparation process, wood is first softened through delignification and then air-dried to close the hollow fibers. Next, a water-shock treatment is applied to partially reswell fibers, making the wood flexible enough to be folded in any desired shape and fixed in place by subsequent air drying. This results in a cell wall-oriented, nanoengineering approach that opens the possibility of wood-based building products with complex geometries and improved mechanical strength. [59] In this context, Wang et al. (2021) introduced smart epoxy-based glass fibers into delignified wood to develop a programmable shape-memory transparent wood, which imparts shape recovery and erasure properties. [60]

Demir et al. (2011) prepared luminescent transparent wood with a diffused effect, a highly promising material for indoor lighting. The incorporation of fluorescent, phosphorescent, or electroluminescent moieties allows the design of panels and displays for smart building applications. These moieties, that are the molecular units responsible for the light-emitting behaviour, make luminescent materials convert absorbed radiation into visible light without significant heat generation. [61]

Shifting from luminescent behaviour to electronically responsive transparent wood, Wang et al. (2019) developed a bottom-up strategy to obtain a multifunctional composite by combining delignified wood substrates with Deep Eutectic Solvents (DES), introduced through in situ photopolymerization. This imparted exceptional stretchability, enabling elongations up to 150% without mechanical failure. The incorporation of ionically conductive component within the polymerized eutectic phase further resulted in a stable electrical conductivity, allowing transparent wood to function as a strain- and touch-responsive element under repeated deformation cycles. [62]

Finally, Bisht et al. (2021) developed a UV-resistant transparent wood for outdoor application by incorporating epoxy resin doped with a phenol-derivative UV absorber. Upon irradiation, in fact, transparent wood acquires a yellowish colour, which darkens with the increasing exposure time due to the reactivation of the chromophoric groups of residual lignin as well as with the degradation of the impregnated polymer. Therefore, to allow the application of transparent wood in outdoor spaces, it is important to increase its resistance against environmental degradation and yellowing. [50]

III. ASSESSMENT OF TRANSPARENT WOOD PERFORMANCE UNDER UV RADIATION

Developing more in depth the UV-resistance functionalization of transparent wood is essential to enhance its durability and reliable performance in real-world applications. In outdoor conditions, transparent wood is continuously exposed to sunlight (UV radiation and visible light), temperature fluctuations, water in the form of rainfalls, snow and humidity, and atmospheric pollutants, all factors that lead to irreversible changes under gradual degradation. This process is termed as weathering, which is predominantly a surface degradation phenomenon initiated by UV radiation, and accelerated by secondary factors, either abiotic or biotic. [16]

Wood species behave differently when exposed to UV radiation, and so does their degradation rate. Similarly, the photochemical activity of a wide range of polymers that are commercially available may differ significantly, depending on their chemical composition. Therefore, the weathering effect and degradation of transparent wood are anticipated due to the presence of residual lignin in bleached wood substrates and the susceptibility of the polymeric reinforcement. [16] As described in the previous chapters, lignin exhibits strong light absorption and undergoes photochemical degradation. This process generates secondary carbonyl compounds, resulting in the yellowing effect of the wood surface. Polymers exposed to UV radiation, instead, absorb high-energy photons capable of breaking the covalent bonds within their molecular framework. This initiates a series of photochemical reactions with the production of free radicals and oxidation of phenolic hydroxyls that alter both their chemical composition and optical properties, ultimately leading to yellowing and loss of mechanical integrity. [16] The discoloration effect caused by UV radiation therefore leads to significant decrease in optical transmittance of transparent wood, and this is attributed to the combined effects of the wood and polymer individually. Given the relatively low-to-moderate activation energies associated with the photodegradation of both of them, even slight increases in the ambient temperature may accelerate this degradation processes, further reducing the service life of transparent wood. [16]

The challenges associated with long-term exposure to intense light sources have not been fully addressed yet, which limits the implementation of this new material. With this thesis, the aim is to move a step towards the assessment of transparent wood under UV radiation, ultimately leading to possible applications and implementation strategies.

III. a. STATE OF THE ART

This section reviews the current state of the art of the studies and methodologies used to assess UV-induced degradation in transparent wood materials.

Starting from Jia et al. (2019), the UV stability of transparent wood was examined by exposing to sunlight for 3 weeks the samples, prepared using basswood and epoxy resin. They reported a slight reduction in transmittance in the 400-500 nm wavelength and increase in haze values. There was no significant reduction in the mechanical properties. [63] Qui et al. (2019), in the same year, performed an accelerated weathering test on transparent wood and reported prominent colour changes within the first 6 hours of exposure. This was mainly attributed to PMMA as a result of chain scissions and to the presence of residual lignin. [64]

Wachter et al. (2021) tested transparent wood under UV-C lamps and showed that the most intense degradation occurred within the first 7 days of exposure and then plateaued. Again, the cause was assumed in the oxidation of the acrylic polymer and reactive chromophores of residual lignin. If the

latter initially contributed to UV absorption, it then also underwent photo-oxidation, causing yellowing. [65] Two years later, Wachter et al. (2023) came back to investigate the fire characteristics as well as the biological and UV resistance of an acrylic-based transparent wood. It demonstrated high resistance to decays caused by fungi and to initiation due to fire exposure. Colour and transmittance changes due to UV radiation were intensive only in the first hours of exposure, and then only very gradually; in the medium and long term, they may be assumed gradual and negligible for most applications. [40]

Bisht et al. (2021) moved forward and prepared functional transparent wood by lignin modification of poplar wood veneers followed by infiltration with epoxy resin with an UV absorber. The photostability was evaluated by exposing transparent wood sheets to a UV-A 340 fluorescent lamp in an accelerated weathering test. For a comparison, natural wood, bleached wood, and epoxy resin samples were also subjected to UV radiation. Their extent of degradation was evaluated by measuring color changes with a spectrocolourimetre, chemical changes through FT-IR spectroscopy, and optical transmittance with a spectrophotometre. As expected, the incorporation of an UV absorber in epoxy resin considerably reduced the discolouration and photodegradation of transparent wood. [50]

Recently, Bisht et al. (2024) came back to investigate the natural outdoor weathering effects on the optical performance of transparent wood with the addition of a benzotriazole-based UV absorber into the epoxy infiltration. Samples were exposed to solar radiation over a period of 150 days. The functionalization of transparent wood limited the transmission loss to around 15% and the rate of colour change was comparatively lower than that of 250 hours of accelerated weathering test. This may be ascribed by the fact that natural weathering occurs as a slow process. [16]

III. b. UV-RESISTANCE FUNCTIONALIZATION OF TRANSPARENT WOOD

Inorganic and organic UV absorbers or stabilizers have been commercially introduced to enhance the performance of wood-based composites, plastics, and other polymeric materials by providing photo-protection. These compounds absorb UV light, get into the excited state, and dissipate the energy as either heat or harmless light, or transfer it to another molecule without causing photochemical damage. Their incorporation into transparent wood does not have adverse effects in the optical properties, preserving both transparency and light transmittance, and significantly reduces the effects of natural weathering, thus being highly beneficial in producing durable and weather-resistant composites. [50]

Among the inorganic UV-shielding materials, titanium dioxide (TiO_2) nanoparticles absorb and scatter UV light while remaining transparent in the visible range, making them ideal for optical applications. They are widely used as additives in cosmetics and construction materials due to their strong photocatalytic properties, high stability, and safety. Additionally, the incorporation of TiO2 nanoparticles enhances the thermal insulation properties of the composite due to their intrinsic low thermal conductivity, which interrupts heat conduction pathways, further extending its applicability. [66]

Carbon-based materials are also excellent candidates for UV-shielding properties because they efficiently absorb both visible and UV radiation, providing a further functionality on side to their application as reinforcing filler in polymers. Xu et al. (2024) prepared a fluorescent transparent wood composite with UV-shielding function by encapsulating Carbon quantum Dots (CDs) and epoxy resin into a delignified wood scaffold. CDs are a material used in photoluminescence with low toxicity, hydrophilicity, and UV absorption properties. Taking advantage of the structure of transparent wood and the UV-absorption capacity of CDs, the cellulose pipeline of lignified wood is used as the dispersive medium of CDs and then filled with epoxy resin for composite preparation. [67]

Finally, while often removed during delignification, lignin may enhance UV resistance if partially retained or modified. Mastantuoni et al. (2023), as an example, developed an in situ sulfonation method followed by hot pressing of pine veneers to prepare high-density transparent films with preserved wood composites. These films showed a UV-blocking capability. However, unmodified lignin tends to yellow under UV radiation over time, and therefore surface treatments or stabilizers are often required. [68] Herrera et al. (2023) investigated the potential of lignin-based surface treatments by impregnating samples with different types of modified lignin (kraft lignin, acetylated kraft lignin, and lignin nanoparticles) using a vacuum-assisted process. The treated samples exhibited significantly improved photostability under UV degradation by the reduced color change and surface degradation compared to untreated wood. Additionally, these treatments enhanced the surface hydrophobicity, limiting moisture absorption and improving the overall durability of the material. [69]

III. c. LABORATORY TEST ON DURABILITY OF TRANSPARENT WOOD UNDER UV RADIATION

In this section it is explained how transparent wood samples were prepared and experiment set up to carry out the laboratory test on durability of transparent wood under UV radiation. Final evaluations were carried out by both qualitative and quantitative means.

The transparent wood samples were prepared through a multi-step process combining an alkaline bleaching treatment and polymer impregnation with a two-component epoxy resin. To verify their suitability for subsequent testing, a set of natural, bleached, and impregnated wood sections were examined using the Scanning Electron Microscopy (SEM) technique. They were then exposed to UV radiations in the visible range under dry conditions, together with samples of pure resin. The irradiance, temperature, and exposure configuration were previously determined based on preliminary tests to ensure an accelerated aging effect, representative of natural sunlight. Periodic measurements were collected throughout the test to monitor changes in the optical properties and evaluate the long-term stability of the material.

In the reference to this experimental activity, I had the opportunity to observe the samples-preparation workflow and to follow the subsequent characterization procedure carried out in the laboratory. I was also able to review the preliminary results obtained during an ongoing testing activity at the Politecnico di Torino, as well as assessing the quality of the prepared samples through SEM images. The preparation workflow of sections of the samples to use under the SEM methodology was also part of my observations. This direct involvement allowed me to gain a deeper understanding of both the practical aspects of the different methodologies and the interpretation of the data obtained.

III. c. 1. PREPARATION OF THE SAMPLES

Five transparent balsa wood samples with dimensions of 2x2 cm and a thickness of 1 mm were prepared through an initial alkaline bleaching technique, followed by polymer impregnation with a two-component epoxy resin. The entire bleaching procedure was carried out following the methodology described in the patent "Metodo per lo sbiancamento di legni attraverso agenti alcalini attivanti stabilizzati" (Italian Patent No. IP 102024000023808, issued on 24th October 2024) by Francesca Gullo, Massimo Messori, and Paola Palmero, and released by Politecnico di Torino [70], while the polymer impregnation and curing processes were carried out following the methodology developed at the KTH Royal Institute of Technology and present in the publications by Li et al. (2016) and Zhu et al. (2016). [43] [45] All processes were conducted at room temperature.

Bleaching occurred in a beaker containing an alkaline solution (Fig. 17) at pH 11, prepared by mixing

25 mL of hydrogen peroxide (H_2O_2) with a relatively high concentration of 30% (a) (b), stored at 4 °C, and 25 mL of deionized water (c) (d), both measured with graduated cylinders, and approximately 1.4 g of potassium hydroxide (KOH), weighted on a laboratory scale (e) (f). Samples were then immersed in the alkaline solution and, to ensure a full immersion and uniform exposure, a smaller beaker was placed on top of them as a weight (g) (h). Samples were left in the bleaching solution for 2 to 2.5 hours, during which they gradually became visibly whitish in colour (i).

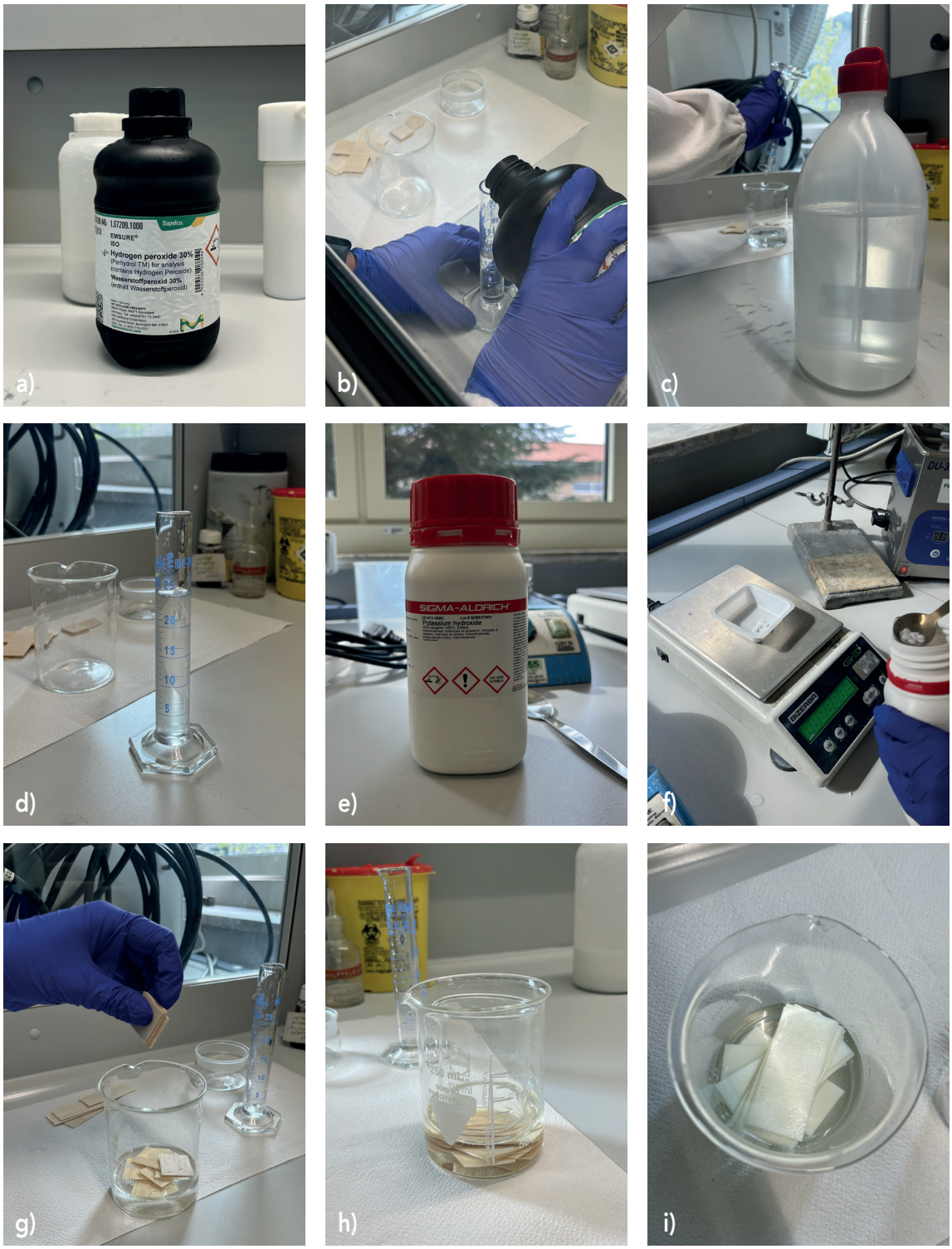


Figure 17. (a) Hydrogen peroxide; (b) Measuring the amount of hydrogen peroxide; (c) Deionized water; (d) 25 mL of deionized water; (e) Potassium hydroxide; (f) Weighing potassium hydroxide; (g) Immersing wood samples; (h) Addition of a smaller beaker as weight; (i) Visibly whitish samples. Photos taken by the author in the laboratory at Politecnico di Torino.

After bleaching, the samples underwent multiple washing cycles to remove residual chemicals (Fig. 18) into a new beaker (a) (b). The initial washing solution consisted of 250 mL of deionized water with 1 g of sodium bicarbonate ($NaHCO_3$) (c), approximately one teaspoon, adjusted to reach pH 9. The samples were then placed under vacuum (d) (e) at a pressure of 250 mbar during washing to facilitate the removal of bleaching agents. Subsequent washing cycles, each one lasting 30 minutes, were performed using deionized water only until the pH of the rinse water reached the neutrality (pH 7). The pH value was monitored using pH test strips (f): they were immersed in the solution for half a second and then compared on the obtained result with the standard colours to determine the pH value by similarities.

Figure 18. (a) (b) Transferring the samples into a new beaker; (c) Washing solution; (d) Vacuum chamber; (e) Washing cycle under vacuum conditions; (f) pH test strip comparison. Photos taken by the author in the laboratory at Politecnico di Torino.

Following washing, the samples underwent a gradual exchange to replace water with less polar solvents (Fig. 19), thus preventing dimensional shrinkage caused by sudden polarity changes, a phenomenon also known as solvent shrinkage. First it was used ethanol (C_2H_5OH) at a concentration of 96% (a) for two cycles of 30 minutes each, and then acetone ($(CH_3)_2CO$) (b) for one cycle only. In both the cycles, the solvent was used in sufficient quantity to fully cover the samples. They were again carried out in vacuum conditions at a pressure of 250 mbar (c). This gradual transition, from the high polarity of water to the nonpolar nature of acetone, allowed for a smoother and controlled dehydration process and prepared the wood structure for impregnation. These steps were fundamental to make the wood scaffold compatible with the polymer, which is naturally apolar, and to eliminate residual moisture, which would otherwise result in incomplete polymerization.

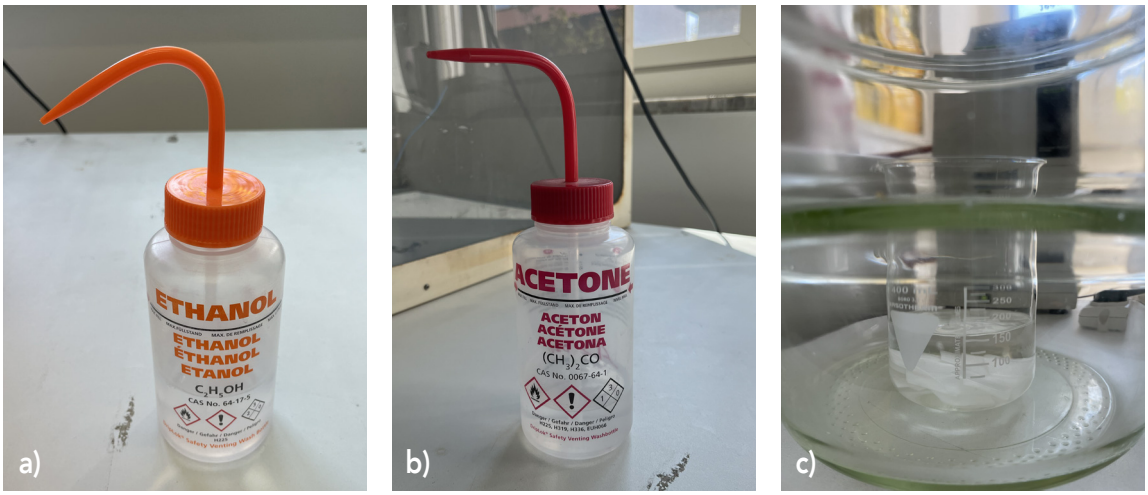


Figure 19. (a) Ethanol; (b) Acetone; (c) Solvent exchange under vacuum conditions.
Photos taken by the author in the laboratory at Politecnico di Torino.

Polymer impregnation then occurred using a two-component epoxy resin with an integrated UV filter (Fig. 20). The component A is the base epoxy resin, which is a viscous epoxy pre-polymer, while the component B is the curing agent. When mixed together, the hardener reacts with the pre-polymer initiating a cross-linking process, that is polymerization, which solidifies the resin into a transparent thermoset network. These two components must be mixed at a weight ratio of 100:60 (A:B). Therefore, for an optimal impregnation, it was considered a resin-to-wood ratio of 5:1 by thickness, so that for the impregnation of five samples of 1 mm of thickness each it was used 20 g of component A (5 mm x 5 = 20 g) and 12 g of component B ((20 g / 100) x 60 = 12 g), weighted on a laboratory scale (a).

The two components were put in a silicon mold to prevent adhesion with the epoxy resin during polymerization and thoroughly mixed using a glass rod. The samples were then immersed in the resin mixture and placed under vacuum at a pressure of 70 mbar (b), which can be considered a stronger vacuum with respect to the previous 250 mbar to enhance resin infiltration into the wood structure. During this stage, bubbles formed on the surface due to acetone evaporation from the samples (c).

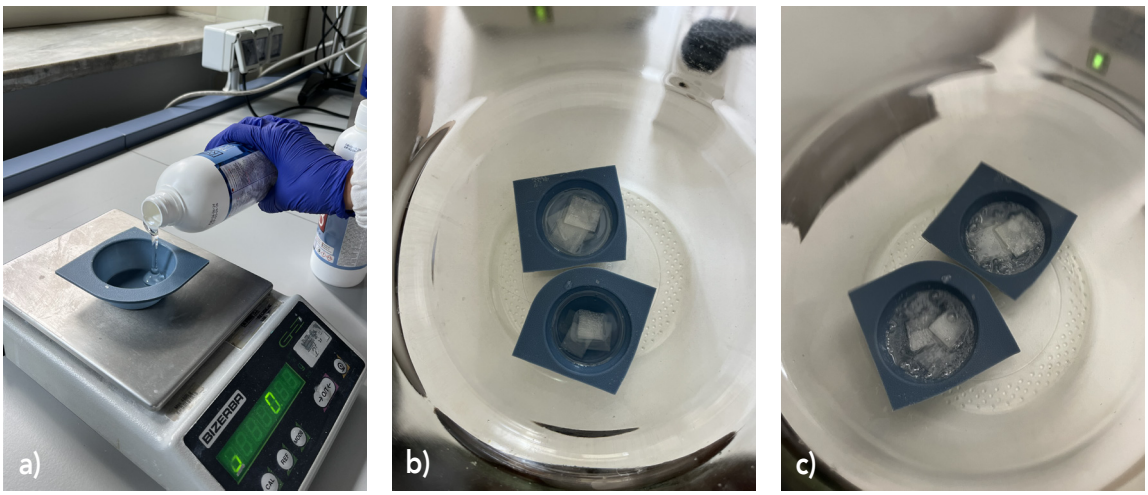


Figure 20. (a) Mixing the two components of epoxy resin; (b) Samples in resin under vacuum conditions;
(c) Bubbles due to acetone evaporation. Photos taken by the author in the laboratory at Politecnico di Torino.

In the meanwhile, some glass slides on which the samples would be later located were prepared (Fig. 21) by applying a release spray to minimize adhesion with the resin (a). After approximately one hour, samples were removed from the vacuum chamber, when the resin was still in a fluid form. A small

amount of resin was deposited onto the glass slides using a disposable pipette (b). The samples were positioned on this layer with the fibers oriented parallel to the longest side of the slide to prevent resin from leaking out (c). An additional thin layer of resin was then applied on top to ensure smoothness and avoid surface roughness or air bubbles.

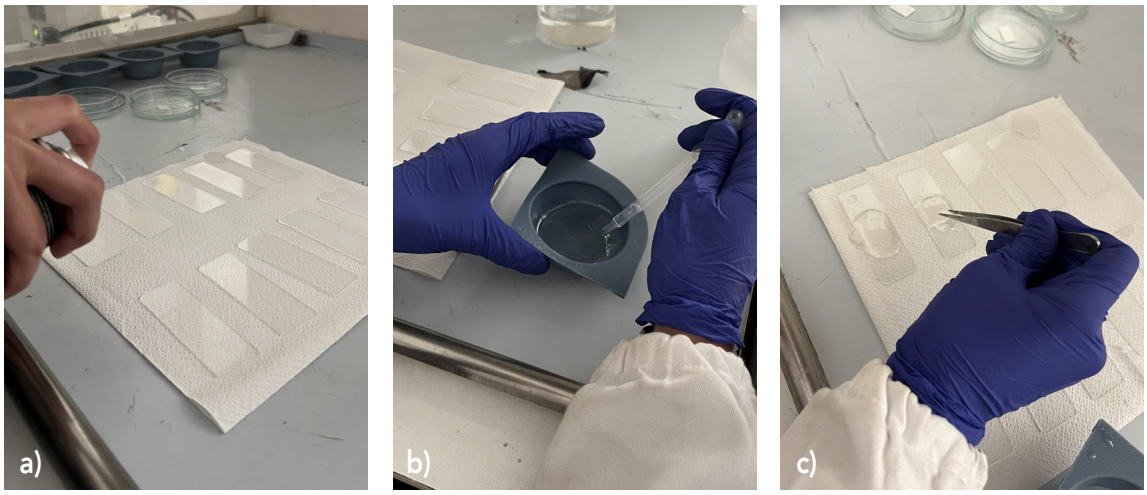


Figure 21. (a) Preparation of glass slides; (b) Taking out resin using a pipette; (c) Positioning transparent wood samples.
Photos taken by the author in the laboratory at Politecnico di Torino.

Complete polymerization occurred after two days at room temperature, resulting in transparent wood specimens suitable for subsequent UV radiation testing.

The different stages of the wood samples according to the preparation stages may be qualitatively appreciated (Fig. 22), from the natural balsa wood samples (a) to the bleached scaffold (b), until the transparent composite after polymer impregnation (c).

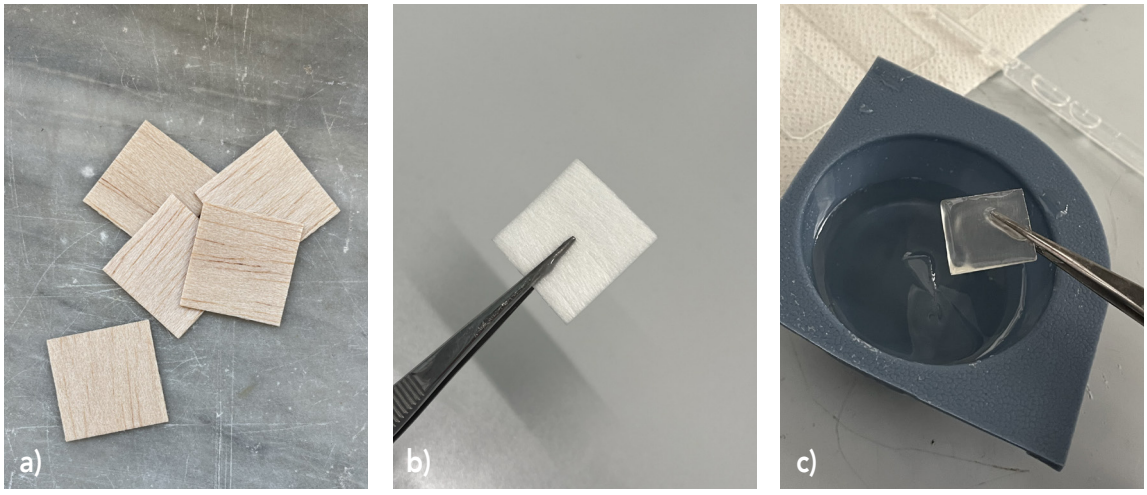


Figure 22. (a) Natural balsa wood samples with dimension 2x2 cm and 1 mm thickness; (b) Bleached wood scaffold;
(c) Transparent wood composite sample after polymer impregnation.
Photos taken by the author in the laboratory at Politecnico di Torino.

III. c. 2. QUALITY ASSESSMENT OF THE SAMPLES

To assess the quality of both bleaching and polymer impregnation processes, sections of natural, bleached, and infiltrated balsa wood were prepared for Scanning Electron Microscopy (SEM) observations. To do so, a Field-Emission SEM (FE-SEM) was used to provide higher resolution, better stability of the beam of electrons, and low-voltage imaging compared to conventional SEM. [71]

Since the SEM technology works with electrons and non-conductive samples tend to accumulate surface electric charge, the samples had to be made conductive in turn to obtain greyscale images with reduced distortion (e.g., bright areas). [71] To do so, each section was mounted on an aluminium stub with diameter of 1 cm, surface coated with double-sided conductive carbon tape to ensure good electrical contact with the sample and minimize charging during the acquisition of images (a). The samples were then fixed in place by applying a slight pressure with tweezers, being careful not to compress the wood porosity in the desired observation area. To further improve the electrical conduction between the samples surface and stub, a small amount of silver-based conductive glue was applied along the contact edges and left to dry at room temperature. It is important to apply the glue only under and on the sides of the samples, and not on top of them, to avoid seeing silver particles later in the images.

Before proceeding with the final stage of the preparation, that is metallization, the mounted samples were dried in vacuum conditions for several hours to remove any residual moisture that could compromise the quality of metal films or generate local heating during deposition, potentially damaging the samples. Metallization ultimately makes the samples surface conductive through the physical deposition of a thin metal film, also called sputtering process, in this case equipped with a gold (Au) target. An inert gas, typically argon, is introduced into the metallizer's deposition chamber after reaching vacuum and, by applying a potential difference between the cathode (metal target) and the anode (chamber), its atoms are ionized. They are therefore accelerated towards the gold target, sputtering metal atoms that then deposit on the surface of the sample. Argon is therefore chosen as a transport gas because it does not react with metal, avoiding oxidizing the target, and has an atomic mass suitable for efficiently knock metal atoms off the target without damaging the target itself or the samples. [71] Each sample was sputter-coated with gold for three consecutive cycles of 1 minute each, which facilitate a uniform coating and reduce the risk of non-conductive areas. The estimated thickness of the deposit film is in the range between 10 and 15 mm, which is sufficient to ensure a good surface conduction without significantly altering the sample microstructure. After all these processes, the mounted samples were inserted in the FE-SEM instrument for analysis (b) (c).

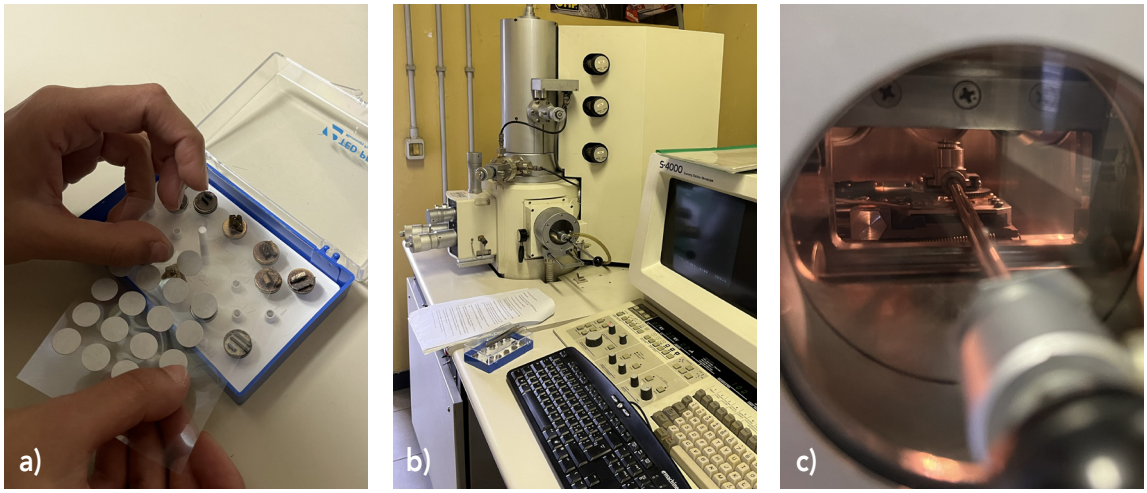


Figure 23. (a) Aluminium stubs and carbon tapes; (b) Field Emission-SEM; (c) Mounted stub placed inside the instrument for analysis. Photos taken by the author in the laboratory at Politecnico di Torino.

From the resulting SEM images (Fig. 24), it is possible to appreciate the differences between natural, bleached, and transparent wood, at different scales. At a scale of 30 µm it is evident the cell wall differences between natural wood, with its full lignin content, and bleached wood, with partial lignin removal that made the lumens larger and more defined in shape. Transparent wood exhibits instead an homogeneous polymerization with no observable zones of incomplete infiltration. Moving then to the 10 µm magnification, it provides an insight on the characteristic changes. Natural balsa wood

micrographs (a) reveal a clear internal organization defined by cell walls and lumens. Areas of lignin retention are visible in the bleached wood (b), and the lumens appear more open compared to the natural sample, indicating the reduction in lignin content. The transparent wood sample (c), finally, shows a complete filling of the lumens with polymer, enhancing a network of cell walls and resin and an optimal preparation of the samples for the conduction of the test.

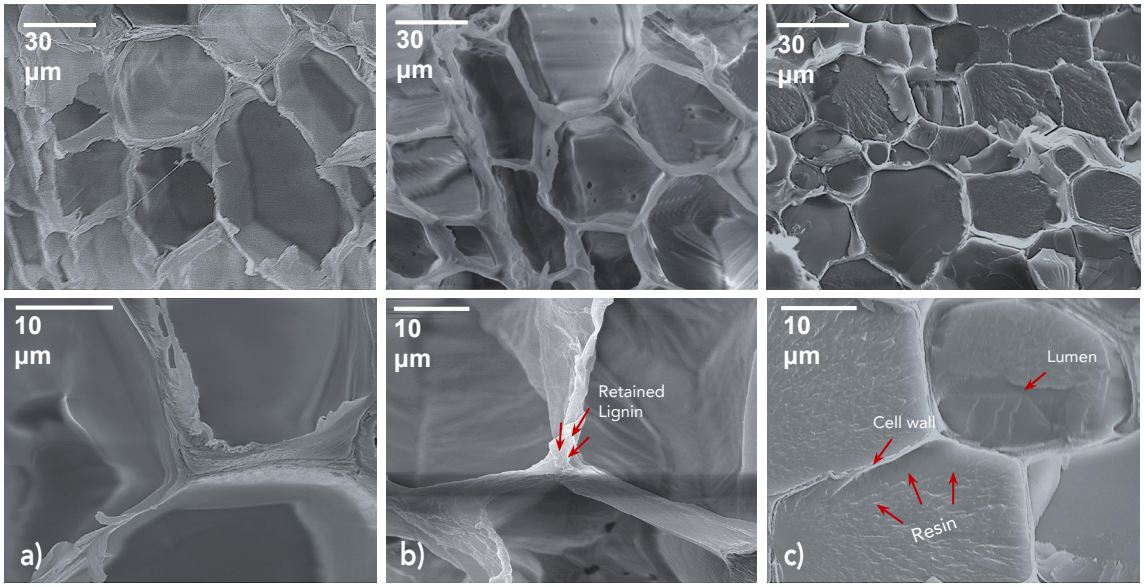


Figure 24. (a) Natural wood; (b) Bleached wood; (c) Transparent wood composite. Photos taken at Politecnico di Torino.

III. c. 3. EXPERIMENTAL SETUP

To conduct the test on durability of transparent wood under UV radiation, the EN ISO 4892-2-2013 standard was taken as a reference. [72] In particular, the test was performed in dry conditions, with 24 hours of daily exposure and no humidity cycles, corresponding to the exposure type no. 5. Preliminary tests were conducted to determine the optimal exposure conditions and to avoid damaging the prepared samples. Furthermore, to obtain a complete evaluation on the performance of transparent wood samples, the test was carried out also with samples of natural and bleached wood and of the same resin used for the preparation of transparent wood. Not only, samples of transparent wood prepared with a plant-based, eco-friendly resin and of this resin alone were included in the set to compare the efficacy of a green alternative with respect to traditional resins. The bio-based transparent wood samples were prepared following the same methods and technique described before in the preparation section.

The samples were placed inside a Solarbox 3000 E equipped with a xenon lamp operating in the UV visible range (290-850 nm) and with a power of 2500 W. The irradiance on the samples, positioned at a distance of 25 cm, was of 550 W/m^2. The chamber was temperature-controlled at 60 °C. The experiment was conducted over a period of 21 days, equivalent to an exposure of 39 solar days. To convert the test duration into the number of actual days out of the lamp, the following formula, taken from the standard, was used:

$$t_{solar,eq} = (I_{solar} / I_{SB}) \times (24 / h_{solar}) \times t_{SB}$$

where:

$t_{solar,eq}$	equivalent time of sun exposure [days]
I_{solar}	average solar irradiance [W/m]
I_{SB}	average irradiance in the Solarbox [W/m]
h_{solar}	average solar hours of experiment [h/day]

t_{SB} test duration in the Solarbox [days]

Measurements were taken every 7 days, once per week, for a total of 4 measures, including the initial before the beginning of the test.

III. c. 4. RESULTS

To evaluate the performance under UV radiation, and so the durability against yellowing and degradation, the samples were compared by optical inspections and measurements, thus assessing the changes by both qualitative and quantitative means.

Starting from the changes by direct observation (Fig. 25), it is possible to appreciate the difference in colour between Day 0 (a) and Day 21 (b), respectively the beginning and end of the test duration. Natural wood, with its untouched texture and composition, appears more yellow in colour due to lignin photodegradation (1). The same happens for the bleached wood (2) due to areas of lignin retention. The sample of resin with integrated UV filter used to produce transparent wood samples appear almost unchanged (3), while the bio-based resin presents yellowing effects (4) because of the absence of any protection against UV radiation. Similarly, then, transparent wood produced with UV-filtered resin presents a slight yellowing (5), while the one with bio-based resin appears with a great difference in colour (6) due to the combined effect of both lignin retention and the resin.

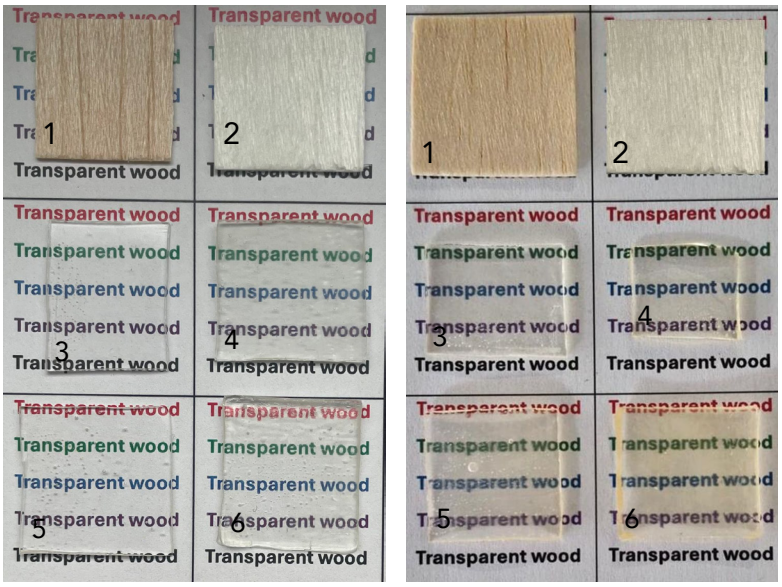


Figure 25. Qualitative assessment between (a) Day 0 and (b) Day 21 of the test.

From a quantitative perspective, the D1003-21 international standard was taken as a reference, in which the test method for haze and luminous transmittance of transparent plastics is evidenced. [73] For taking the measures, it was used the hazemeter instrument, that with an integrating sphere collects both the direct and scattered components of transmitted light. The sample is positioned at a distance from the entrance port of the integrating sphere so that only the light passing nearly straight through the material reaches the photo detector. [4] [74] According to the standard, the formula to calculate the total transmittance is the following:

$$T_t = T_2 / T_1$$

where

T_1 incident light

T_2 total light transmitted by the specimen

Before comparing the different performances of the samples under UV radiation throughout the test period (4 weeks), three graphs were plotted to understand the transmittance values along the visible spectrum at Day 0 (Fig. 26). From the comparison between natural and bleached wood samples (a), it is possible to see that the chromophoric groups present in natural wood absorb light in the range between 400 and 650 nm, as the curve changes its path after that, while bleached wood has a totally different path due to the removal of these groups. For the two resins, the difference is highlighted in the range between 350 and 400 nm: the sharpener curve is due to the presence of UV-filter, while the bio-based resin has a different curvature (b). The two transparent wood composites, instead, show a similar pattern but two different initial transmittance values (c).

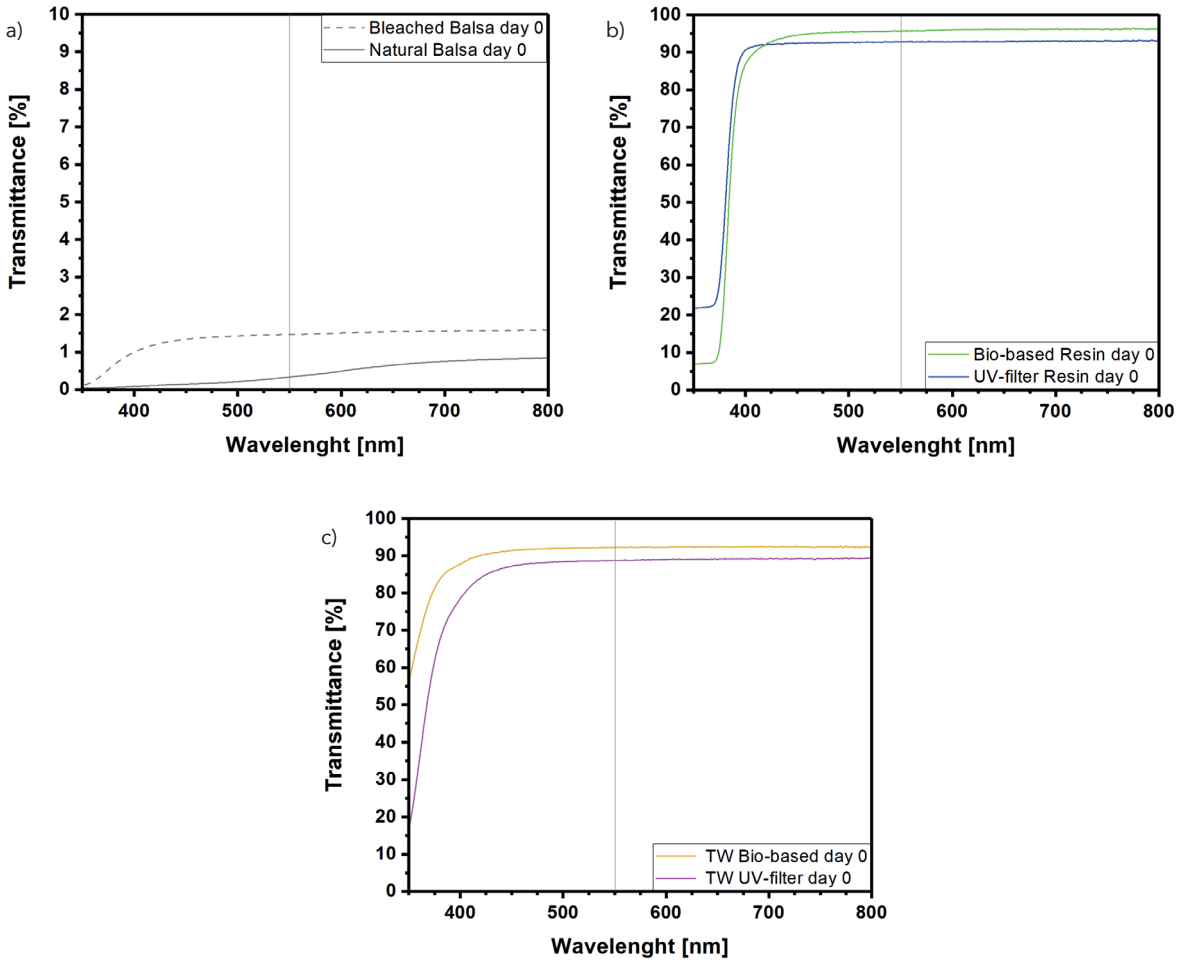


Figure 26. Comparison of transmittance values of the samples at Day 0 in the visible spectrum.
(a) Comparison between natural and bleached balsa samples; (b) Comparison between UV-filter and bio-based resin samples;
(c) Comparison between transparent wood composite samples with UV-filter and bio-based resin. Graphs produced by the author.

After calculating the total transmittance (T_t) for each wavelength, it was chosen the 550 nm value for comparing the performance of the samples. This is the literature value of reference because it corresponds to the peak of sensitivity of the human eye and lies near the centre of the visible spectrum.

For natural wood, the transmittance remains almost constant (Fig. 27) because it does not significantly age under UV exposure. For the bleached sample, instead, we would expect a decrease in value because it tends to yellow over time, as it is possible to perceive from the qualitative assessment. However, the observed trend is the opposite, and this happens because of the bleaching treatment: once the chromophoric groups are chemically removed (along with part of lignin, which normally protects the wood from UV radiation), the wood begins to age and yellow. The exposure further accelerates this removal, which leads to an increase in transmittance. Therefore, even if the bleached

wood samples tend to yellow over time due to the physical ageing of wood, transmittance increases because other chromophoric groups are removed.

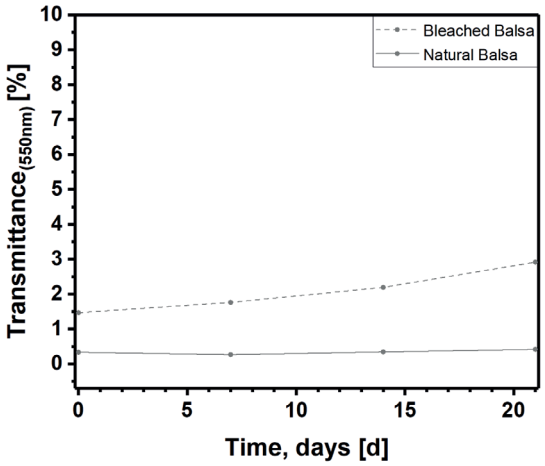


Figure 27. Comparison of transmittance values of natural and bleached balsa at 550 nm wavelength. Graph produced by the author.

At Day 0, the composite made with the UV-filter resin shows a transmittance value almost overlapping with the one of the pure resin (Fig. 28). As the exposure continues over time, instead, the two samples exhibit completely different trends: the composite's transmittance decreases, while the one of pure resin remains nearly unchanged. The decrease in the composite occurs because of the dual effect of both resin and wood under UV radiation, as the UV-filter in the resin gradually loses effectiveness and wood ages. Wood is inherently more susceptible to ageing because of the removal during the bleaching process of part of the lignin, which provides protection to UV radiation. Between the second and third week there is a little further change, suggesting a possible stabilization of the trend, although this hypothesis must be confirmed with longer-term testing.

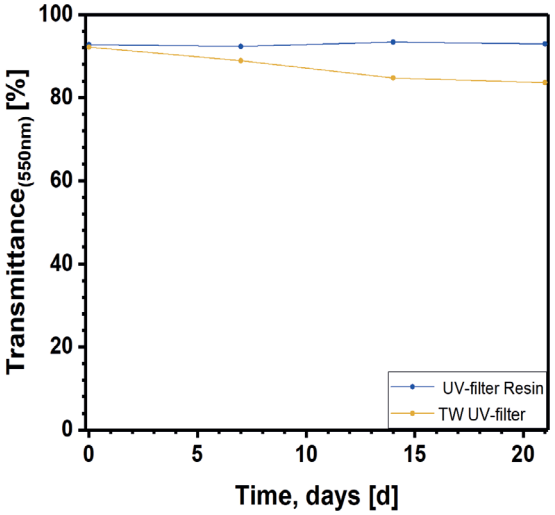


Figure 28. Comparison of transmittance values of transparent wood composite with UV-filter resin and pure UV-filter resin at 550 nm wavelength. Graph produced by the author.

Finally, analysing the behaviour of transparent wood composite prepared with bio-based resin and pure bio-based resin sample (Fig. 29), the overall trend is always decreasing because neither the resin nor the composite contains a UV filter. Furthermore, the transmittance value of the composite at Day 0 is lower with respect to the one of pure bio-based resin. This may be attributed to an optical mismatch in refractive index between the wood scaffold and the impregnated resin; therefore, the refractive index difference is greater compared to transparent wood made with UV-filter resin. In the composi-

te, the decrease in transmittance is more pronounced during the first week, after which the decline becomes more gradual.

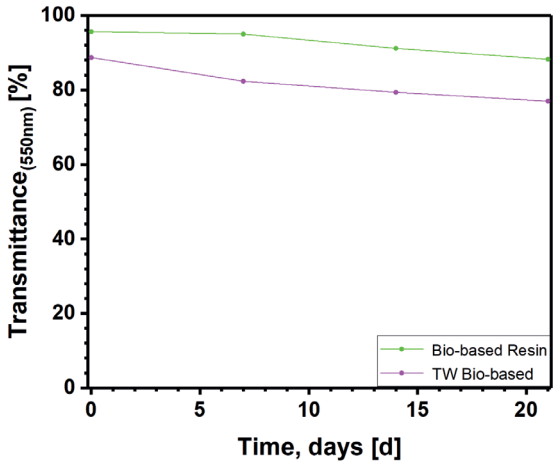


Figure 29. Comparison of transmittance values of transparent wood composite with bio-based resin and pure bio-based resin at 550 nm wavelength. Graph produced by the author.

Overall, the combined qualitative and quantitative analyses highlight how the optical stability of the different samples used for this test under UV radiation depends on both the intrinsic chemistry of the wood scaffold and the resistance ability of the resins. The qualitative inspection already suggested what was later confirmed by measurements: the lignin content and the presence of chromophoric groups play a major role in colour changes in wood, especially in natural and bleached wood where yellowing is strongly associated with photodegradation processes. The comparison between resins further emphasises the importance of functionalization for maintaining optical clarity. The UV-filter resin remains largely stable throughout the testing period, while the bio-based resin without any shielding shows progressive degradation, directly correlating to reduced durability. When incorporated into transparent wood composites, the UV-filter resin displays a slight decline in transmittance due to both resin and wood contributions. However, compared to transparent wood composite prepared with bio-based resin, it presents an excellent performance of resistance under UV radiation, denouncing its suitability for applications with UV exposure.

IV. IMPLEMENTING TRANSPARENT WOOD IN ARCHITECTURAL RESTORATION

Transparent wood is rapidly gaining attention as a material innovation and its primary application lies in the building sector. [75] Trees and transparency are two elements that have not been connected so far, but developments in materials science have made their path converging, changing also the perception of how materials can be tailored to specific functions and requirements. Although the current status still presents some limitations, particularly regarding the scalability of the production processes, the aim of this section is to imagine a future in which the following applications can be realized and propose unrestrained ideas.

Within this forward-looking framework, it is essential to revisit the role of innovative materials not only in terms of new constructions, but also in restoration and retrofitting interventions, thus reimagining the past with current considerations. The growing demand for sustainable, high-performance materials in architecture and design has intensified the already-existing interest in bio-based composites capable of surpassing the inherent limitations of traditional materials. Among these developments, transparent wood has distinguished itself as a promising alternative to address contemporary requirements.

IV. a. PRINCIPLES OF ARCHITECTURAL RESTORATION

The selection of materials in architectural restoration represents a crucial phase as it directly affects both the physical integrity and the cultural significance of the built heritage. [76] The sensitivity that a restoration intervention requires, therefore, must be transmitted also in the choice of the materials to be used. In this context, decisions regarding the introduction, replacement, or integration of new materials must follow widely recognized principles and align with the historical, structural, and aesthetic context of the building. Compatibility with the existing materials, reversibility and minimum intervention, and visual and historic coherence constitute the fundamental framework guiding responsible restoration practices. [77]

Compatibility is intended as the chemical, physical, and mechanical congruence between the original material and the new one to avoid harmful interactions, such as different coefficients of thermal expansion or the onset of chemical reactions that could favour degradation. [77] In historic wooden structures, this issue becomes particularly relevant as timber is hygroscopic and in continuous moisture exchange with the surrounding environment. This means that aspects including dimensional stability and durability under UV radiation must be carefully considered when implementing new materials like transparent wood. [76] [78]

Equally significant are the principles of reversibility and minimum intervention, which determine the modern conservation theory following the Venice Charter by ICOMOS in 1964, one of the foundational documents in the field of architectural conservation as it established its universal principles and defined the ethical basis of modern restoration. [77] Reversibility requires every intervention to be removable without damaging the pre-existing, thus ensuring that future interventions, equipped with improved knowledge and techniques, can reinterpret the action. [77] This aligns with the definition of restoration by Cesare Brandi in his book "Teoria del restauro", published one year before the Venice Charter, in which he stated that restoration *"constitutes the methodological moment of recognition of the work of art in its physical consistency and in its dual aesthetic-historical polarity, with a view to its transmission to the future"*. [79] With regard to the materials, it implies favouring solutions that do not permanently alter or damage the existing fabric.

Finally, the third essential criterion is visual and historical coherence, which relates to the aesthetic, cultural, and contextual integrity of the heritage asset. [77] The challenge lies in balancing the legibility of the intervention with respect to the existing character; therefore, making the intervention clearly distinguishable. Materials must integrate with the building in a way that respects its architectural values, and their selection is evaluated according to the desired degree of continuity or contrast with the historic materiality. [77] In some cases, transparent wood may support a coherent integration due to its natural affinity with timber-based structures, while in other its innovative and contemporary appearance may intentionally signal a new layer of intervention. In both the scenarios, the goal is to ensure that the architectural narrative of the building remains comprehensible.

All these criteria together form a comprehensive framework for evaluating the suitability of restoration interventions and their materiality. When applied to new materials like transparent wood, they support a rigorous and informed approach that balances the technological innovation with respect for the built heritage.

IV. b. ASSESSING TRANSPARENT WOOD AS AN ALTERNATIVE TO GLASS IN WINDOWS

Glass has long been a symbol of transparency and versatility in human craftsmanship, and from construction to packaging its applications span a variety of industries and daily life. Not only for its transparency, but also due to its chemical inertness, availability, durability, and comparatively low costs, it represents one of the most widely used materials in buildings, especially for windows. [80] However, glass production is not a sustainable process because of its high energy requirements and associated carbon emissions. In fact, the melting of raw materials such as silica, sodium and magnesium carbonate, limestone, and dolomite requires temperatures ranging from 1500 to 1600 °C, during which the decomposition reactions release a large amount of carbon dioxide (CO_2), posing environmental concerns. [80]

The use of glass also presents several disadvantages, among which there are glare, sharp shadows, and shattering. Regarding glare, defined as the extreme contrast of brightness, the human eye cannot adapt to such unsuitable light distribution, causing a significant visual discomfort and poor emotional well-being. In cities where buildings are equipped with large-format glass windows and façades, strong light reflections may be directed to the eyes of pedestrians and vehicle drivers, causing visual fatigue and even traffic accidents. Similarly, glass produces well-defined shadows, contributing to the overall discomfort in indoor spaces. [81] Shattering, instead, poses safety issues due to its fragmentation into splinters or shards. Its high brittleness causes cracks to expand easily, making delicate the handling, installation, and use due to accidental impacts. Conventional silica glass thus requires lamination or coatings to achieve enhanced safety performances, increasing both weight and costs. [81] Not only, with a density of ≈ 2.6 g/cm^3, it presents drawbacks in terms of transportation and handling. The relatively high weight not only increases logistical and installation costs but also demands more robust supporting structures. In contrast, transparent wood offers a substantially lighter alternative, typically exhibiting a density around 1.2 g/cm^3, reducing mechanical load and enabling a safer installation. [82]

Finally, the high thermal conductivity of glass (≈ 1.0 W/mK) results in a lower energy efficiency with respect to transparent wood (≈ 0.19 W/mK). [83] [84] In order to achieve an adequate insulation, it is required the use of insulating systems, such as double or triple glazing with a sealed air- or gas-filled cavity between the panes, or secondary glazing installed on the interior side of existing windows.

Now having a look at modern requirements, as evidenced in the second chapter transparent wood may be functionalized according to the desired properties. In this context, Li et al. (2017) tested the

application of transparent wood in smart windows by fabricating it with Polymer-Dispersed Liquid Crystals (PDLC). The optical properties were adjusted using an electric field by changing the alignment of crystals; when there was no electric field the window showed high haze, privacy protection, and a limited amount of light entering, while when the power was on the window became transparent. [82] Transparent wood, therefore, may be used as a substitute for glass in buildings for either visual clarity (low haze) or privacy protection (high haze), while glass relies on additional coatings or technologies once more.

All these characteristics of glass are compared with those of transparent wood, analysed in detail in the previous chapters, in the following table, tailored to their application in windows:

	GLASS	TRANSPARENT WOOD
Transparency	*High transparency, clear visual transmission*	*Adjustable light transmission up to 95%*
Optical performance	*Causes glare; may lead to visual discomfort and poor emotional well-being*	*Naturally-diffused transmission reduces glare, improved visual comfort*
Privacy control	*Relies on coatings*	*Adjustable haze (high for privacy)*
Thermal conductivity	*High; ≈ 1.0 W/mK*	*Low; ≈ 0.19 W/mK*
Smart window potential	*Requires additional coatings or technologies*	*Demonstrated potential using PDLC systems (Li et al., 2017)*
Weight	*Relatively heavy*	*Lightweight*
Density	*High; ≈ 2.6 g/cm^3*	*Low; ≈ 1.2 g/cm^3*
Chemical properties	*Chemically inert*	*Polymer matrix, sensitive to UV radiation unless functionalized*
Durability	*Long-lasting, resistant to weathering*	*Good durability but requires UV stabilisation*
Mechanical properties	*Brittle, cracks spread easily*	*Tough, absorbs energy*
Safety	*Shattering risk, dangerous fragments*	*Safe under impact*
Production process	*High-temperature melting of raw materials (1500-1600 °C), environmental impact*	*Low energy requirements, can be conducted at room temperature*
Sustainability	*Energy-intensive production, high CO_2 emissions*	*Lower embodied energy, bio-based, renewable, potentially biodegradable*

Table 6. Comparison between glass and wood for use in windows.

Transparent wood, therefore, presents several advantages over traditional glass when applied in window systems. However, it does not only have to meet the basic requirements of glass when used in its place, such as adequate light transmission and weather resistance, but also compensate for its disadvantages and shortcomings, including high thermal conductivity and brittle failure (Fig. 30). Transparent wood has to achieve a consistent level of performance, and this includes meeting recognized standards. [85] Through an appropriate stabilization of its properties, together with the development of preparation protocols and testing procedures, it has the ability to turn into a reliable and technically validated material with the potential to fulfil demands of window applications in both contemporary and heritage contexts.

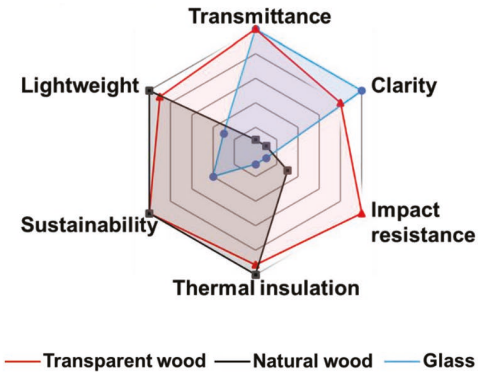


Figure 30. A radar chart that compares the various properties of transparent wood, natural wood, and glass. Reproduced from [84] under the licence ID 1676509-1.

IV. c. SELECTED APPLICATIONS OF TRANSPARENT WOOD IN ARCHITECTURAL RESTORATION

In this section transparent wood is explored as an alternative to glass in historic windows, a replacement of decayed wooden structural elements, a reinterpretation of furniture and decorative artifacts, and a multifunctional component in museum and exhibition spaces. These potential applications, while still largely hypothetical and in the need of further testing, open up to how emerging bio-based materials may reshape future approaches to restoration and architectural expressions.

IV. c. 1. ALTERNATIVE TO GLASS IN HISTORIC WINDOWS

Heritage and listed buildings were typically constructed using traditional materials and methods that may not meet modern energy-efficiency standards. Among the common related issues are the single-glazed windows (Fig. 31), which contribute to significant energy loss and related high heating and cooling costs. [75] Slim-profile double glazing developed specifically for historic windows; however, these solutions are not always compatible with historic frames, which often cannot accommodate the additional thickness and weight without compromising their structural integrity or altering their original appearance. By replacing original glass with a more efficient transparent material, it is possible to maintain the building's authentic character and pairing it with energy-saving technologies.

Figure 31. Window with single-pane glass and thin frame. [86]

After the comparison between the performances of glass and transparent wood in window applications, it is evident how the latter has the potential, in the future, to be used as a viable alternative with tuneable characteristics. In particular, in restoration interventions, it offers a promising solution due to its low thermal conductivity, impact resistance, low weight, and possible functionalization. The tuneable haze values of transparent wood offer a great innovation over glass. The creation of panels that transmit light while diffusing it, thus avoiding glare and sharp reflections, is particularly valuable

in heritage contexts where visual comfort, interior preservation, and improved control of solar heat gains must coexist. Furthermore, this system is also applicable for roof lanterns and skylights, where safety performance as well as diffused light are beneficial for these types of applications.

Beyond the substitution of individual panes, transparent wood could also be used as a self-standing panel in fixed windows, owing to its high toughness and mechanical strength. This opens the doors to the possibility of designing frameless or minimally-framed fixed windows in small to medium-sized openings, provided that its overall performance is adequately addressed. From an architectural restoration perspective, the use of transparent wood as a self-supporting panel is particularly interesting, for example, for openings where the original frame got lost.

IV. c. 2. REPLACEMENT OF DAMAGED WOODEN STRUCTURAL ELEMENTS

Transparent wood that retains part of its lignin structure may be particularly suitable for load-bearing or semi-structural applications, like beams or roof panels, where mechanical strength is of fundamental importance. Its enhanced mechanical performance thus open new ways in the conservation and consolidation of historic wooden structures, where original elements may have experienced degradation over time.

As evidenced in the first chapter talking about the durability of wood, fungal attacks represent the most worrying cause of decay, compromising the integrity of structural elements. In these cases, few curative treatments exist and among these is the removal of damaged parts and their replacement with some prostheses. The selective use of transparent wood elements represents a new restoration strategy that maintains a direct continuity and ensures the compatibility with original wood, while at the same time clearly identifying the restoration intervention. This not only preserves the overall aesthetic and historic character but also introduces a visually engaging layer that reveal the underlying wood structure. However, a careful hygro-thermal and structural design must be carried out to ensure a good compatibility between transparent wood and natural wood also in terms of thermal expansion and dimensional stability, which can be achieved by properly selecting thermoset polymers with low shrinkage strain.

The intrinsic transparency of this new material permits a detailed 3D reconstruction and non-destructive evaluation of the structural behaviour. Architects and engineers can then assess stress distribution, identify micro-failures, and monitor the mechanical performance over time. Furthermore, although transparent wood retains much of the original structure, its susceptibility to fungal decay is lower with respect to natural wood, thus reducing the risk of further degradation in the future. This is due to both the chemical modifications in the preparation process, which remove completely or partially lignin, that is the natural component that fungi typically target, and impregnation with polymers, which are naturally resistant to biotic decay.

This possible application of transparent wood gives credits do Diederik Storms, a Dutch sculptor known for his hybrid works that merge natural organic materials with transparent media. The contrast between the rough texture of wood is juxtaposed with the smooth clarity of resin (Fig. 32), producing a tension between what is visible and what is not. Light furthermore plays a role by entering the clear elements, creating a dynamic visual experience. [87]

Figure 32. Sculpture by Diederik Storms. [87]

IV. c. 3. FURNITURE AND DECORATIVE COMPONENTS

When applied to partition walls, transparent wood gives the opportunity to separate interior spaces while maintaining light transmission, thus reducing reliance on artificial lighting and mitigating the common trade-off between spatial division and illumination typical of conventional opaque partitions. High haze values, as mentioned earlier, increase light diffusion, softening shadows and blurring silhouettes, thus enhancing privacy. Such properties enable the deliberate and more flexible arrangement of internal divisions that reinforce the autonomy of each zone, especially in large rooms, and spatial perception. All these aspects contribute to a more engaging and comfortable interior design.

When used in furniture, transparent wood intersects emerging technologies with long-standing traditions of woodwork as both structural and expressive medium, enriching the spatial, environmental, and aesthetic qualities of interior spaces. Its visual effect derives not from a uniform, synthetic clarity, but from an interplay between the preserved lignocellulosic microstructure and the refractive behaviour of the polymeric matrix used to fill the lumens. This combination produces a perceptible depth and textural luminosity that differentiates transparent wood from both traditional wood and conventional transparent panels, supporting design approaches that value sensory richness and material legibility. In this regard, the reproduction of historic furniture using transparent wood, for example, introduces an additional interpretative dimension: it gives the idea of what existed while signalling the contemporary nature of the intervention. This deliberate use of transparent wood generates an ephemeral reminder of the original artifact, enabling designers to evoke historical memory without resorting to literal imitation.

A significant exploration of this emerging potential took shape in the exhibition "Wood x Transparency?", held in Tokyo in January 2024. Originated from the collaboration between the Musashino Art University and the Shiseido Mirai Research Group, and supervised by the designer Wataru Kumano and lecturer Saei Honda, the exhibition functioned as both a learning environment and research-driven exploration of wood's material. Transparent wood was used as a way to investigate how transparency can redefine traditional understandings of wooden artifacts. [88] The prototypes ranged from small-scale objects to larger architectural elements, among which there is the hinoki bath chair from Mina Namba (Fig. 33). It reinterprets the shape of the traditional cypress bath chair, familiar to many Japanese as part of the hot spring tradition, creating a more hygienic version with less sensitivity to moisture. The exhibition ultimately demonstrated that the fusion of wood and transparency is not merely a formal experiment but also a methodological shift in design thinking. [89]

Figure 33. Hinoki bath chair made by transparent wood by Mina Namba. [88]

IV. c. 4. MUSEUM AND EXHIBITION SPACES

In museum and exhibition spaces, where the combination of visitor experience and artifacts showcase is critical, transparent wood provides an innovative material to balance these competing requirements. These spaces often accommodate high visitor flows, with a great potential in generating mechanical energy through daily movements. Due to the uniaxial orientation and lack of a centre of symmetry of the semi-crystalline cellulose fibrils, wood is referred as a natural piezoelectric material. When crystals undergo mechanical stress, the asymmetric arrangement of charges within the crystal network produces a net electric polarization, converting low-grade mechanical energy, such as vibrations or small temperature gradients, into an electrical output. [90] This property can be exploited in restoration interventions to develop self-powered lighting or sensor systems within the exhibition areas, enhancing sustainability and energy efficiency. Recent studies demonstrated that the piezoelectric response of wood may be enhanced by increasing wood compressibility through delignification: the selective removal of lignin from balsa wood resulted in highly compressible wood sponges with a piezoelectric output 85 times higher than native wood, making transparent wood, which relies on lignin removal or modification strategies, an ideal ally for this function. [91] [92]

Transparent wood may also be used as protective architectural panels in exhibition systems. This applicability comes from the rare combination of optical tunability, mechanical strength, and UV resistance, when appropriately functionalized. The latter is a central performance criterion for conservation as many organic artifacts exhibit accelerated degradation in the UV wavelengths, which may be prevented through the incorporation of protective filters or surface protective layers. [93] Furthermore, the low thermal conductivity of wood permits a more controlled and uniform temperature distribution within sealed environments, reducing moisture-related risks.

Not only, through its functionalization in the preparation process, transparent wood has the potential to integrate electronics in the reinforcement matrix. In this context, Timothée Boitouzet, an architect who turned into a material entrepreneur, founded the WooDoo company to develop an "augmented" wood that could host conductive pathways and touch interfaces. According to the company's technical descriptions, this approach enables the incorporation of sensors, lighting elements, and interactive controls, while preserving the tactile and visual qualities of the original material. [94] It is therefore possible, in the field of architectural restoration, to introduce interfaces and display-related technologies in ways that are materially coherent with the historic interiors, without appearing overly modern or out of place.

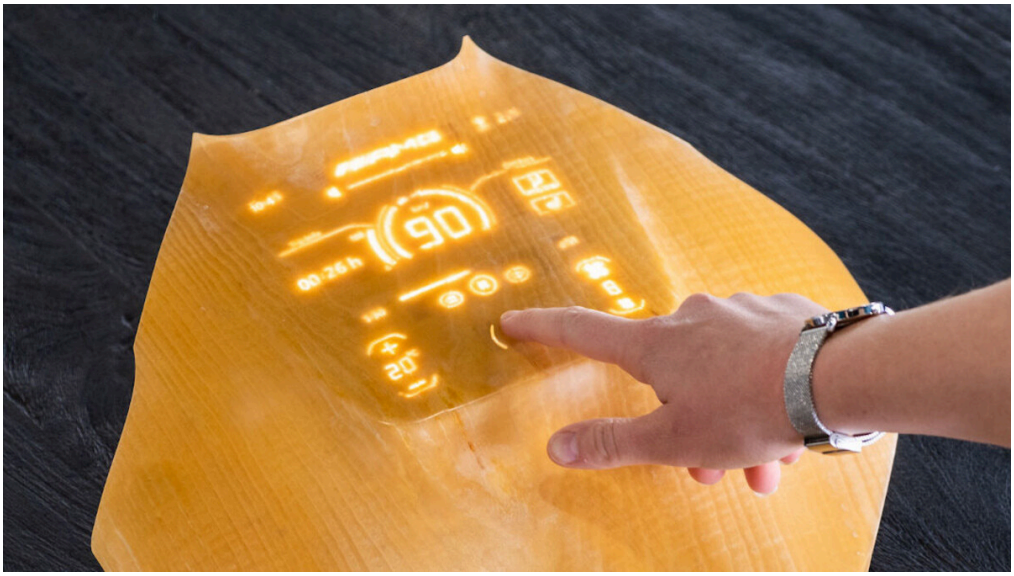


Figure 34. Augmented wood by WooDoo. [94]

IV. d. FUTURE PROSPECTS

Transparent wood has demonstrated a remarkable potential as a bio-based alternative to traditional building materials. However, despite a decade of research, scaling up its preparation process remains a challenge, still facing several technical, environmental, and economic issues. Understanding these limitations is essential to guide future prospects and ensure an efficient, reliable, and sustainable manufacturing.

One of the major limitations lies in the scalability of the delignification and bleaching processes. It is difficult to ensure uniform chemical infiltration and treatment in large samples, and excessive processing could compromise the mechanical stability of wood by thinning the cell walls or exposing nanocellulose fibers. Ultimately, delignification represents a delicate balancing act: it must remove or modify lignin sufficiently to achieve transparency, while preserving the cellulose-based skeleton and ensuring that the process remains environmentally sustainable. Future progress will likely depend on combining chemicals with biological methods, like enzymes, optimizing the bleaching protocols. Beyond delignification, also the infiltration of the polymer matrix presents challenges. Ensuring a complete impregnation in thick samples requires long processing times and vacuum-assisted systems, raising the preparation costs. Furthermore, the adhesion between polymer and cell wall is affected by any residual lignin and moisture of the previous steps, ultimately influencing the mechanical strength and optical homogeneity of the samples.

Long-term environmental durability is another open debate. While this thesis aimed at contributing to this issue, also other studies have evaluated UV radiation resistance of transparent wood, and some other will have to. Polymer yellowing, photodegradation of residual lignin, and dimensional changes due to humidity may be mitigated through targeted functionalization to enhance the performance.

Finally, beyond the technical aspects, economic and logistical factors also play a key role. The cost and availability of suitable wood species can vary depending on the region, and adapting existing wood-processing infrastructure to transparent wood preparation requires investments and innovative ecosystems. The collaboration between academia, industry, and policymakers will be vital to ensure a scalable, economically viable, and sustainable production of transparent wood.

On a systemic level, the main issues related to the scalability of transparent wood preparation are:

- High production costs due to the multi-step and time-intensive preparation processes;
- Reliance on chemically intensive treatments, which raise also environmental concerns;
- Limited sample thickness, constrained by both delignification and polymer impregnation uniformity;
- Standardization issues, lacking unified optical, mechanical, and durability benchmarks for transparent wood materials.

Looking forward, several pathways hold promise for the transition to real-world applications:

- Sustainable processing approaches using green solvents, enzymatic treatments, and bio-based resins;
- New functionalization strategies, like the incorporation of surface modifications;
- Waste utilization of byproducts from the preparation processes;
- Multilayer transparent wood products through the stacking of thin veneers, offering an improved mechanical performance and more predictable optical properties;
- Research and systematic studies to further expand both the theoretical and experimental aspects of this new material.

V. REVISITING AN ARCHITECTURAL DESIGN THROUGH THE ADOPTION OF TRANSPARENT WOOD

The restoration project of the Priory of Athassel, one of the most evocative monastic complexes in Ireland, emerged as an exploration of how contemporary architecture can engage with the historic fabric through minimal intervention and material sensitivity. Central to this approach was the use of charred wood and brass metal, both chosen for their expressive contrast and ability to reveal the pre-existing without hiding it.

The design of a modular exhibition case for the former chancel, repurposed into a museum, became a key component of the project's conceptual and material investigation. Inspired by Carlo Scarpa, the sculptural interplay of voids, steps, and carved geometries permits to host artifacts of different dimensions with high adaptability. Its composition, which uses the same materials as the entire restoration project, stands as an autonomous piece of craftsmanship.

By rethinking about this design, the introduction of transparent wood represents not only an alternative to traditional glass for the protection and support of objects, but also as a means for enhancing the characteristics of the exhibition case. This draws theoretical inspiration from Franco Minissi's pioneering use of transparency as a restoration strategy to obtain reversible, non-intrusive means of protection while offering a new interpretation of archaeological remains. The use of transparent wood, therefore, is both an innovation and an homage to wood is all its declinations, from the structure of the case to the charred finishing.

V. a. THE RESTORATION PROJECT OF THE PRIORY OF ATHASSEL

Nestled on the western bank of the River Suir near the village of Golden, County Tipperary, The Priory of Athassel (Fig. 35) stands as one of the most evocative monastic ruins in Ireland and its complex mirrors the rise, influence, and gradual dissolution of the medieval religious life.

Founded around 1200 by Lord William de Burgh, the monastery was established for the Augustinian Black Canons and dedicated to St. Mary and St. Edmund the King and Martyr, who reflect the typical pattern of Norman piety. During the 13th and 14th centuries, it evolved into a religious and social hub whose spiritual significance was reinforced by its role as a burial place for influential members of the de Burgh family. Homes and workshops clustered around its walls. [95] The priory later suffered two destructive fires, both of malicious nature. Each episode inflicted a significant damage on the infrastructure and eroded its capacity to function as a cohesive religious community. By the late 15th century, signs of decay started to appear, and canons began to live in individual, private dwellings rather than within the monastery, contributing to its poor maintenance. [95] Despite these setbacks, the Priory of Athassel remained an officially recognized religious house until 1537, when it was finally dissolved under the Reformation and its buildings were left to fall into ruin. [95] Even after this decline, the priory continued to gain attention and artists like George Victor Du Noyer depicted it into drawings.

Inside the fortified precinct, approached via a medieval bridge and gatehouse, stood a monumental church, cloisters, dormitories, refectory, chapter house, and all the structures that defined a full Augustinian community. The church was particularly impressive with a cruciform layout with nave, transepts, and a tower at the crossing. South of the church lay the cloister, around which clustered the living quarters, the chapter house, refectory, and living spaces for the canons. From this central spine, the priory radiated outward.

Figure 35. The Priory of Athassel from an aerial view (top) and from the nave looking at the tower (bottom). [96]

It is in this context that the restoration project of the Priory of Athassel came out. As a result of a high-level training course in "Architecture for Heritage" that I attended in 2022, this project was carried out under the tutorship of Valerie Mulvin from the McCullough Mulvin Architects studio, an innovative contemporary architecture and urban design practice based in Dublin, and in collaboration with three teammates, Isgandar Hajiyev, Anqi Pan, and Ruth Adalgiza Iacob.

The principles that governed the project were those of architectural conservation and minimal intervention, where the approaches reveal rather than replace, and visitor-oriented experiential path. Starting from an analysis of the site, it was possible to reconstruct the various historical layers that followed one another over time, including those now reduced to ruin. This understanding clarified the complexity of the site and guided the interventions. The project's design idea was to allow the visitors to experience the priory both vertically, through the reconstruction of the tower, and horizontally, through the open nave and chancel museum. Furthermore, an attentive choice of materials fell on charred wood, reminiscent of the history of the priory and as a weather-resistant finishing, and brass metal, used to denounce the details of the intervention and chosen to contrast with the rough, black wood. Following is a masterplan (Fig. 36) that identifies all the major architectural interventions:

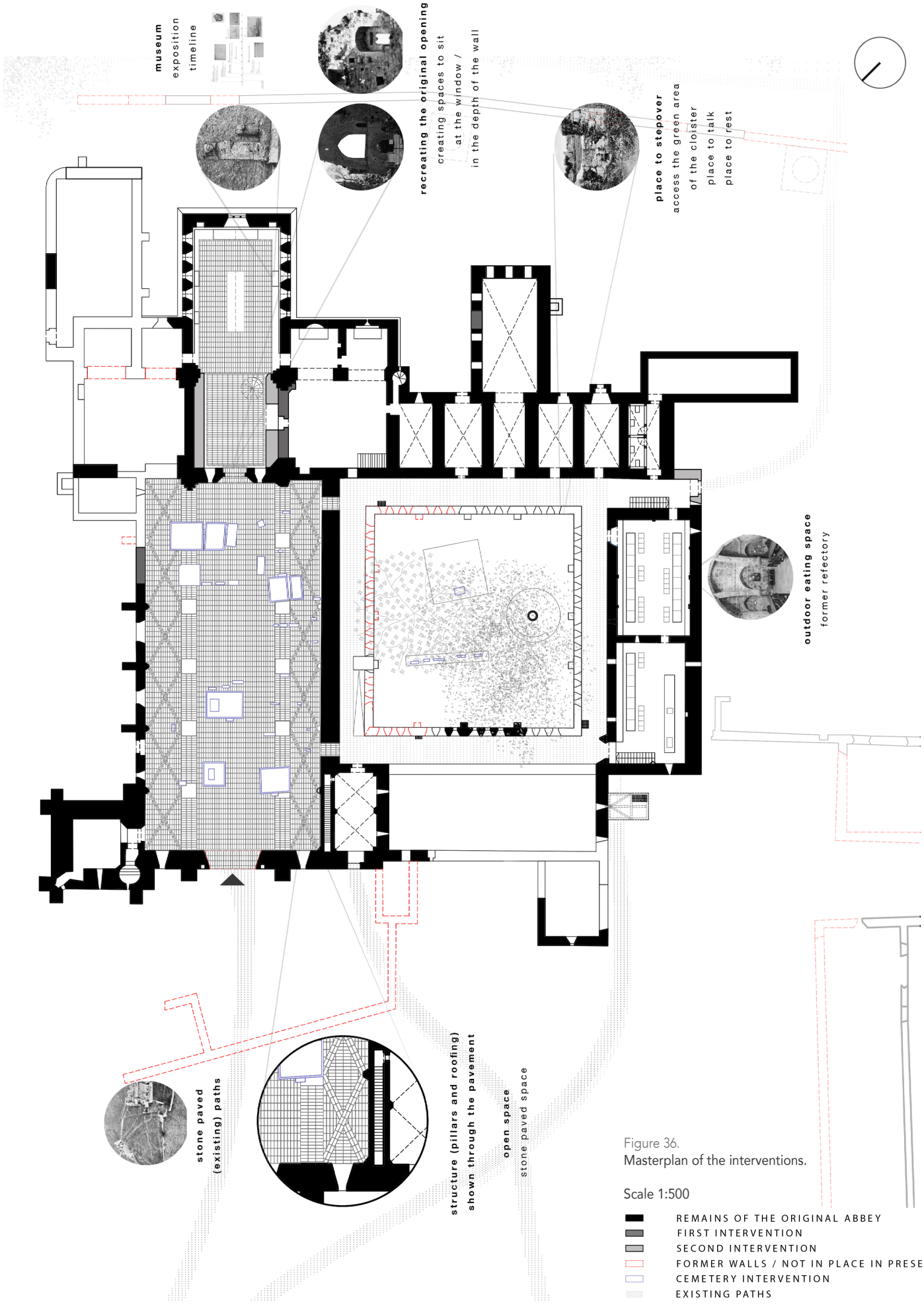
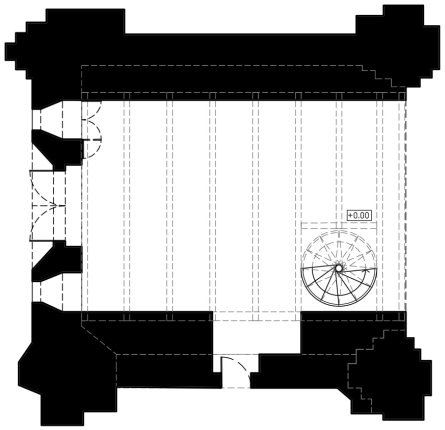


Figure 36.
Masterplan of the interventions.

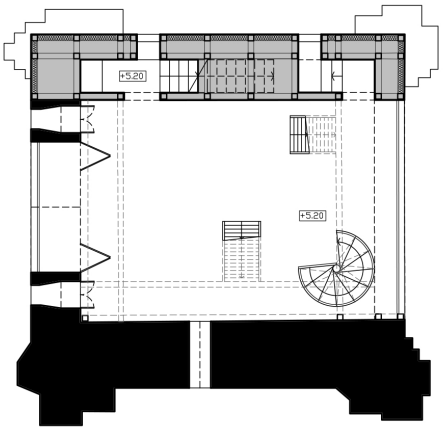
The entrance to the Priory of Athassel occurs through the nave (Fig. 37), which is today an open space. By stone paving it, the first intervention sees the representation of the original structure on the floor like if it was an architectural plan. Therefore, the pillars are denounced in their original position through brass metal squares on the ground, the arches are two parallel lines connecting the pillars, while vaults are represented with the typical cross that reflects the groins.

Figure 37. Collage representing the restoration of the nave and the reconstruction of the tower. Drawing by the authors.

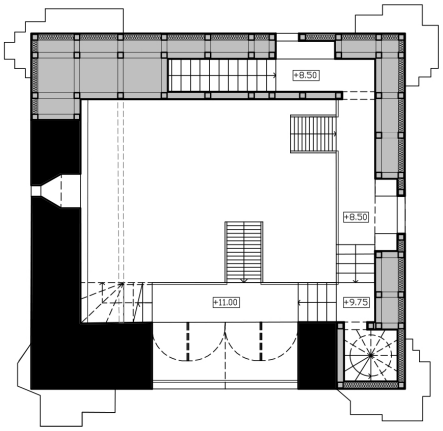
After crossing the nave, a major intervention focused on the reconstruction of the tower, introducing an exploratory internal circulation (Fig. 38) (Fig. 39). A spiral staircase wraps around a metal core and brings to the first platform at level +5.20 m. Through an always-changing design of each platform, visitors can pause, sit within the wall cavities, or access small terraces, an interpretation of Luis Kahn's notion of "walls as floors" where the structural mass becomes inhabitable space. At the uppermost level, that is +18.40 m, visitors can have a walking experience on the existing wall as it directly lies on its thickness, offering a unique panoramic view across the monastic complex and landscape. This intervention creates a new ritual of movement, a gradual shift from enclosed spaces to open vistas, revealing the scale and geometry of the ruined tower.



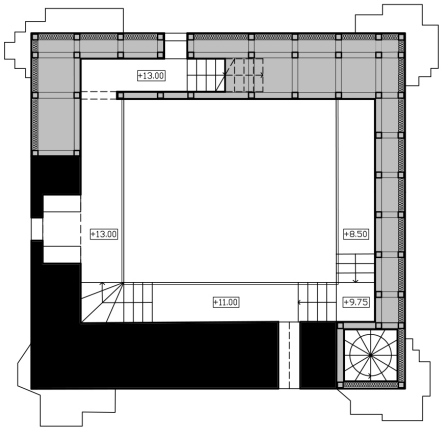
±0,00
choir performance



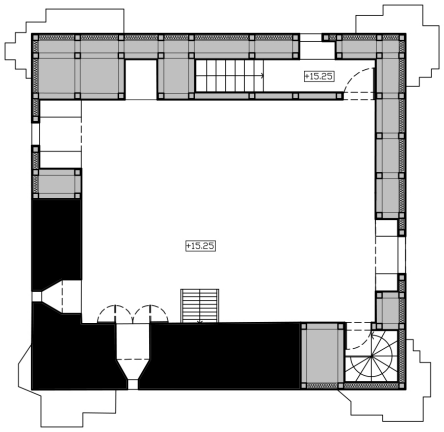
+ 5,20
solo performance
perspective towards the museum



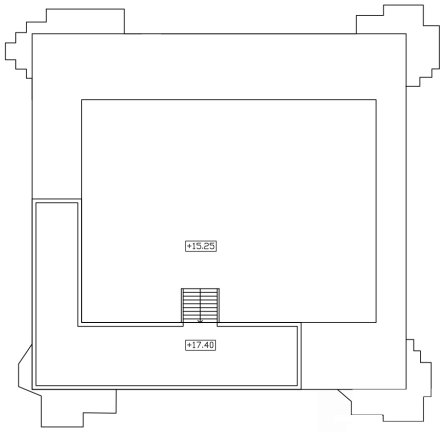
+ 8,50 / + 11,00
small platforms and
wall cavities / spaces to sit



+ 13,00
small platforms and
wall cavities / spaces to sit



+ 15,25
uncovered room / terrace with walls
and wall cavities



+ 17,40
walk on the walls and top view

Figure 38.
Plans of the different levels of the reconstructed tower.

Scale 1:200

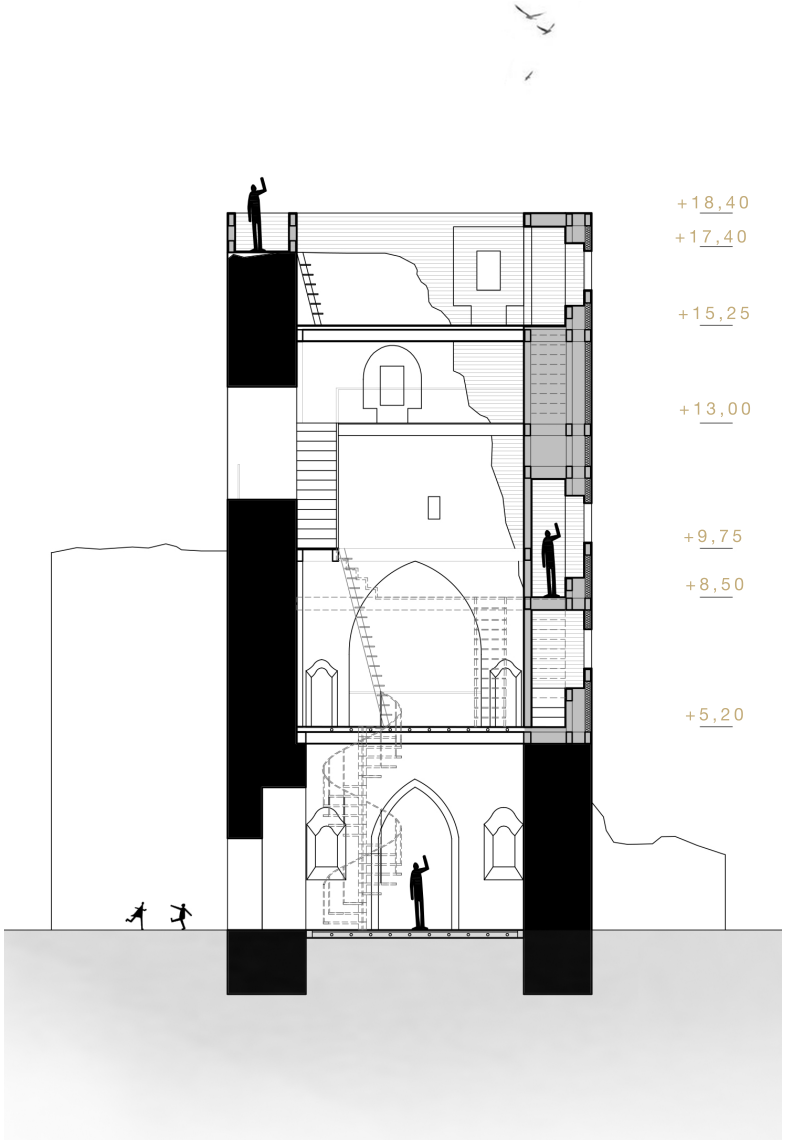


Figure 39.
Section of the reconstructed tower.

Scale 1:200

After the tower there is the former chancel, which was repurposed into a museum (Fig. 40). This is the only space intended to be closed, and as such represents another major intervention in the complex. By following the principle of reversibility, an insulated timber roof structure finished with charred wood lightly shelters the space lying on the existing walls, unframed glazing closes the windows geometries, and a heated decking system ensures year-round usability while resting on the existing walkway. The new pavement has been intentionally left not to cover the entire surface, as an offset of the perimeter, to denounce the nature of the intervention. In this outline, statues are elevated on brass metal bases, reinforcing the idea of a minimal, respectful insertion. In the middle of the room, finally, an exhibition case in intended to show objects related to the history of the priory, or as a temporary exhibition of other artifacts. This piece of furniture design will be extensively analysed in detail in the subsequent section.

Figure 40. Collage representing the restoration of the chancel into a museum. Drawing by the authors.

All these interventions, which lie on the same line of action, represent the core of the restoration of the Priory of Athassel as it was envisioned, with architectural conservation and minimal intervention, and offer an exhaustive expression of its principles and materiality.

V. b. THE EXHIBITION CASE INSPIRED BY CARLO SCARPA

The exhibition case, intended for the chancel restoration and repurposing into a museum space, aims at hosting both artifacts from the Priory of Athassel as well as temporary installations. This curatorial flexibility demanded a highly adaptable display system, leading to the conception of the exhibition case as a modular composition capable of being arranged together or separately according to the different needs. Adaptability was also declined for the display areas, so that each module incorporates a variety of carved spaces and surfaces able to accommodate objects of different scales and orientations. The inspiration at the base of this design comes from Carlo Scarpa, a sophisticated

Italian architect whose interventions had global resonance. In particular, it comes from his Brion Memorial masterpiece in the province of Treviso (Fig. 41), a place of silence, peace, and harmony, where the experiential continuity transcends the static nature of the building. The interplay of concave and convex forms and the architect's iconic stepped motifs were borrowed for the final design of the exhibition case, as well as the insertions of brass metal elements as detail.

Figure 41. Brion Memorial in Altivole. Photos taken by the author.

The design consists of a module of 90x90 cm, built from a wooden structural frame assembled using dry joints and finished with charred wood panels. A thin stepped pedestal of 5 cm elevates the block. On top, instead, lays a stepped half-pyramid, measuring 45 cm in length and 55 cm in height. The final composition presents dimensions defined by the golden ratio (Fig. 42).

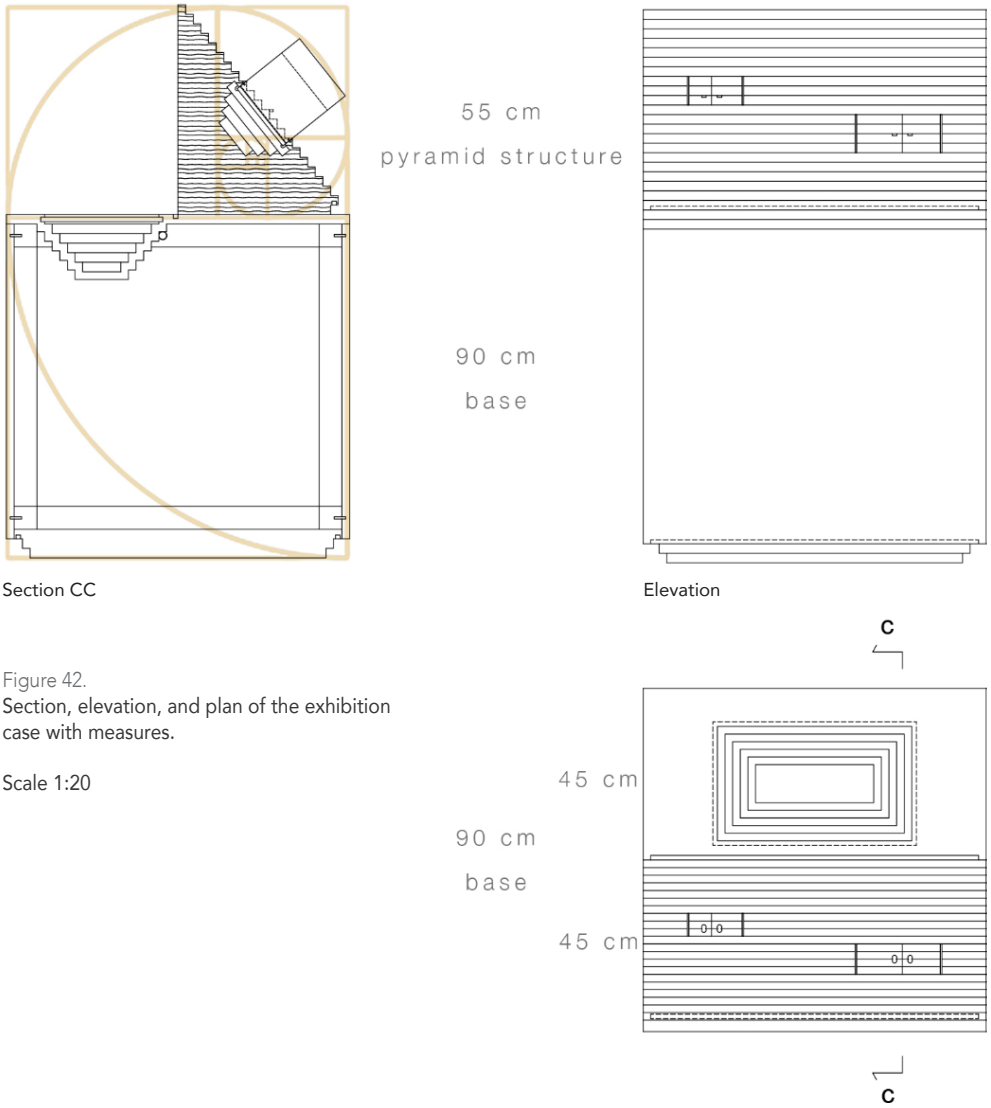


Figure 42.
Section, elevation, and plan of the exhibition case with measures.

Scale 1:20

The pyramid, being cut in half, occupies half of the top surface of the block, so that the other half could be carved through steps (Fig. 43), creating a deliberate contrast between convex and concave, solid and void, a tension that Carlo Scarpa used to enrich both functionality and aesthetic.

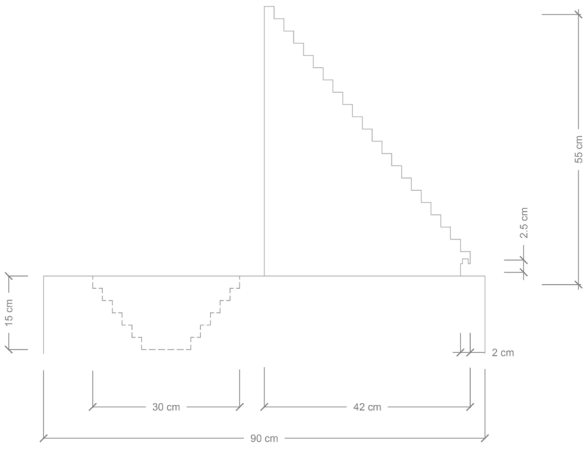


Figure 43.
Drawing representing the stepped half-pyramid and the carving display area.

Scale 1:20

Both the carving and the pyramid operate as versatile display systems (Fig. 44). In the first case, taking advantage of the steps, shelves of different dimensions are laid on different steps to create a smaller or larger surface according to the object size that is going to be displayed. This allows to range from small pins to books. Within the pyramid, instead, the stepped excavations support objects at a slight incline, giving them both stability and visibility (Fig. 45).

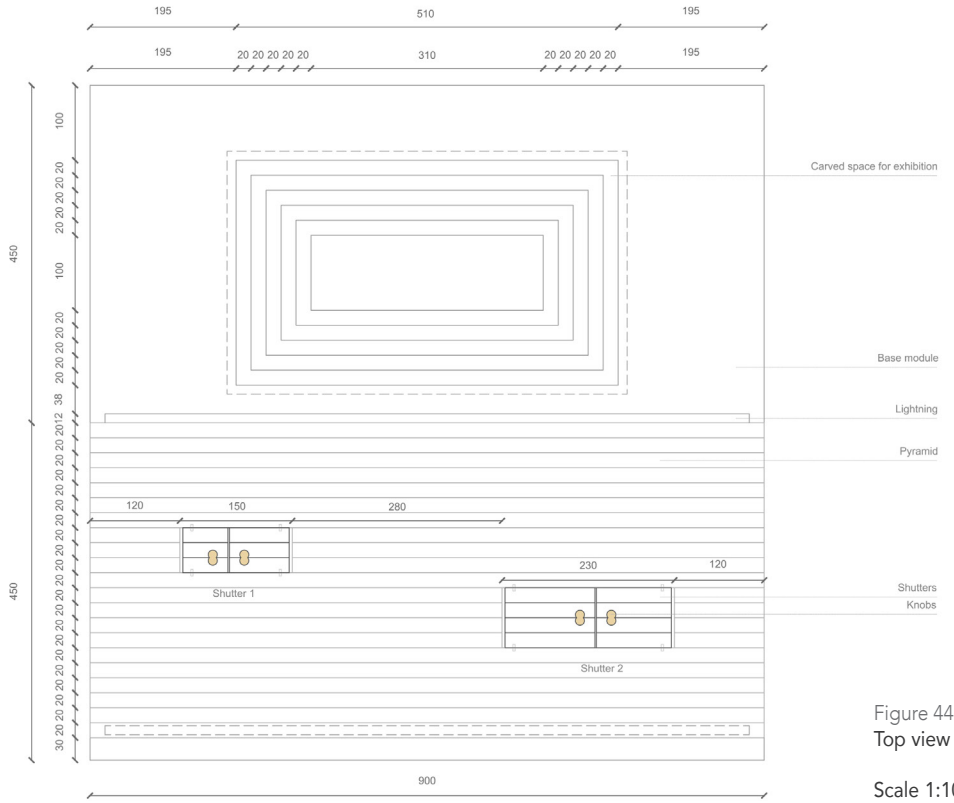


Figure 44.
Top view of the module.

Scale 1:10

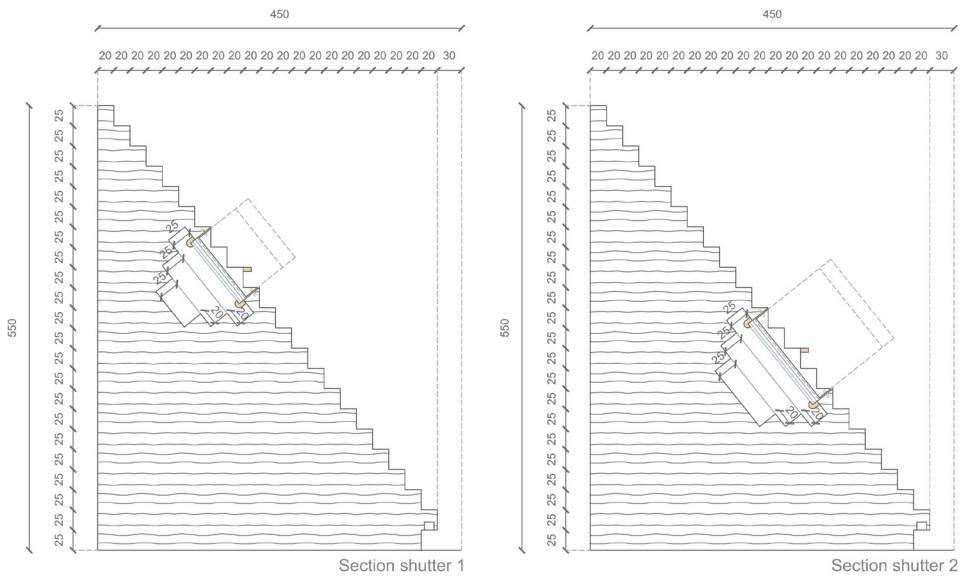


Figure 45.
Section of the two shutters showing the carvings, and glass panes with their brass metal supports.

Scale 1:10

The glass panes rest on brass support elements, and thanks to the natural inclination of the display surface, no additional fixing is required (Fig. 46).

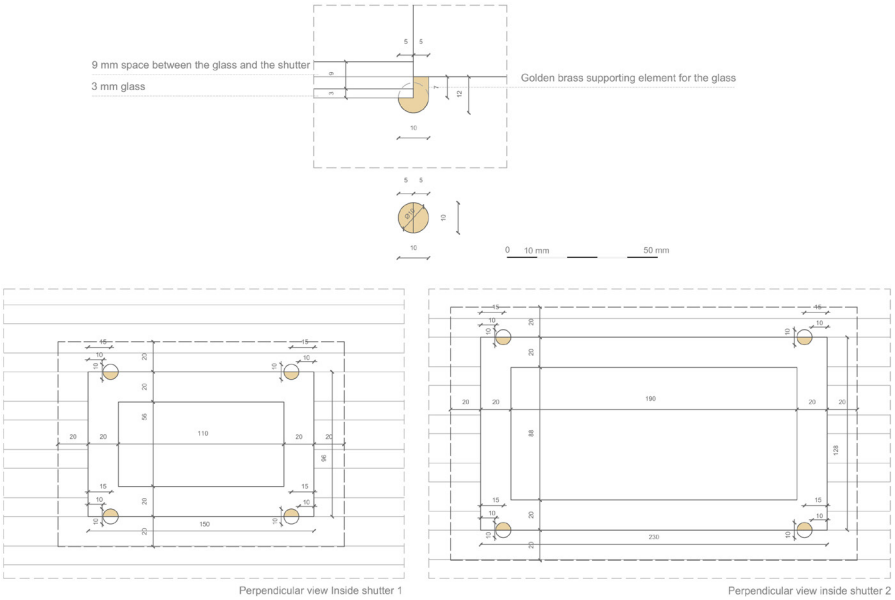


Figure 46.
Detail of the brass metal element supporting the glass panes.

Scale 1:5

The shutters of these display areas, operated by elegant brass metal knobs shaped as arcs of a circle (Fig. 47), introduce an interactive dimension in which visitors can choose to reveal what is inside. When closed, the shutters restore the pure geometry and appearance of the pyramid but denounce their presence through the knobs.

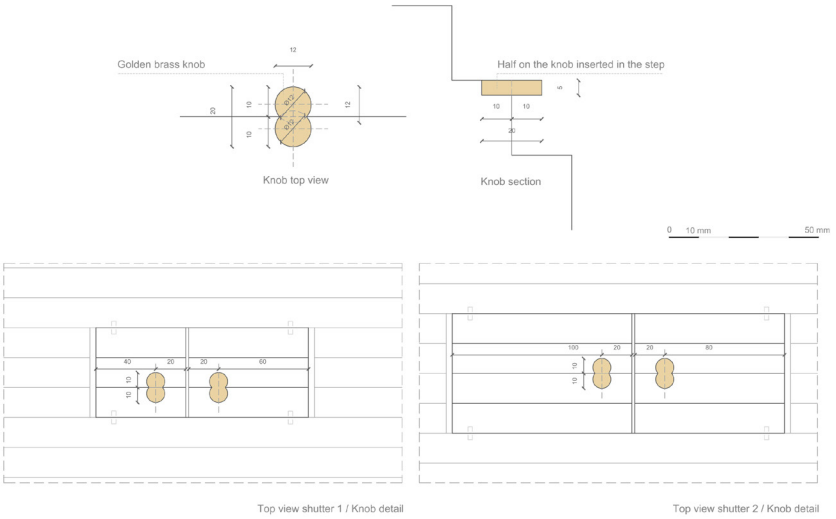


Figure 47.
Detail of the brass metal knob.

Scale 1:5

The choice of materials and their colour further enhance the exhibition case not only as a display medium but as a piece of art itself. While the exterior finishings are made of charred wood, the internal carvings reveal the natural brownish colour of wood, immediately signalling where the objects are. Additional brass elements define the composition, offering both functional and ornamental accents. The exhibition case, in the end, offers continuity with the restoration of the Priory of Athassel, while at the same time being adaptable to very different contexts, like the colourful Sammezzano Castle in the provice of Florence (Fig. 48).

Figure 48. Collage of the exhibition case in the Sammezzano Castle. Drawing by the authors.

This design has been effectively realized in collaboration with Cesare Roversi Arredamenti and its prototype presented publicly during the Fuorisalone 2023 in Milan. The theme "Laboratorio del Futuro", which promoted a space for dialogue and experimentation where sustainable design, material innovation, and emerging technologies become tools to imagine and build responsible futures.

V. c. REINTERPRETING THE EXHIBITION CASE THROUGH TRANSPARENT WOOD

The exhibition case is presented here as an example of how a museographic design can be reinterpreted through the introduction of emerging innovative materials and contemporary technological advancements. The decision to replace traditional glass with transparent wood resonates with the theoretical approach of Franco Minissi, whose pioneering restoration strategies from the 1950s onward emphasized the use of transparent media, especially glass and Plexiglas, as reversible, non-intrusive devices. For him, transparency was not merely a practical solution but a conceptual tool: it allows protection while coexisting with archaeological remans without visually competing with them, thus preserving the legibility of the ancient fabric while introducing a controlled layer of interpretation. [97]

Inspired by this conceptual framework, the notion of transparency is reinterpreted through transpa-

rent wood, an innovative bio-based material that preserves the perceptual clarity while overcoming some limitations of traditional glass. Mechanically, transparent wood offers a superior impact resistance, reducing the risk of shattering and improving safety for both visitors and artifacts. The operable shutters within the stepped half-pyramid can be executed with significantly greater control and reliability than would be possible with glass. Not only, it provides safety in the handling of the panes when putting in place or removing artifacts from display areas.

Beyond its use as a protective layer, transparent wood is also employed in the carved portions of the exhibition case. Here the shelves, originally conceived in natural wood, are reinterpreted through thin transparent wood planes that function as supports rather than closures. This enables visitors to perceive the depth of the stepped geometries and visually explore the carving, which provides a suggestive background to the exposed objects. Transparent wood thus becomes an instrument for amplifying spatial legibility, transforming the carved geometries into luminous, permeable displays.

On the back of the pyramid, which forms a vertical wall, a transparent wood panel of 5 mm thickness is applied and functionalized to operate as an interactive display surface. This integration extends the material's potential from mere structural and protective roles to a technologically advanced interface. A linear LED lighting element beneath the panel is positioned in a dedicated carved line to ensure the correct functioning of the embedded electronics: interactive systems require a stable and uniform light source to guarantee readability, enhance contrast of digital content, and adjust brightness. This backlighting system thus stabilizes the luminous conditions needed for accurate operation of the interactive display while preserving the overall aesthetic coherence of the exhibition case.

Transparent wood also demonstrates optimal thermal insulation qualities, typically three to five times higher than those of traditional glass. This property is essential for preventive conservation as the stabilization of microclimatic conditions mitigates condensation and minimizes abrupt temperature fluctuations that may threaten artifacts. Combined with UV-filter functionalization, as detailed in the laboratory testing of this thesis, transparent wood becomes an effective barrier against UV radiation, surpassing traditional glazing solutions and contributing to long-term material preservation.

While glass frequently produces glare, reflections, and mirror-like effects that disrupt visibility and require additional artificial lighting, transparent wood distributes light homogeneously, minimizing visual interference. This provides a more accessible display environment for every visitor as the absence of strong reflections ensures that the object remain clearly visible across different viewing angles without relying on additional processing or coating. Furthermore, the material's warm appearance, with subtle traces of grain that remain perceptible, integrates harmoniously with the surrounding finishings. This visual coherence is reinforced by the fact that the entire exhibition case is constructed from wood, from the structural frame to the charred wood for the panels and natural brownish wood for display areas. In this sense, the introduction of transparent wood in the exhibition case becomes not merely a functional material choice but an homage to wood in all its declinations and enormous potential.

Finally, from an environmental perspective, transparent wood presents significant sustainability advantages. As a renewable, bio-based material with a comparatively low embodied energy, its production contrasts sharply with the energy-intensive processes required for glass. In this, the material aligns with contemporary ecological requirements, supporting the project's commitment to sustainable, non-intrusive design practices.

This work ultimately aims at demonstrating the importance of rethinking materials as an integral component of the contemporary architectural restoration practice. Innovation does not only mean looking ahead but also coming back to traces. Revisiting historical knowledge, reinterpreting strategies, and returning to own projects to reconsider them through a new lens is crucial. The substitution

or integration of traditional materials with contemporary solutions constitutes an exercise that does not negate the original design intents but instead expands its potential and opens the doors to conceptual, technical, and environmental refinement.

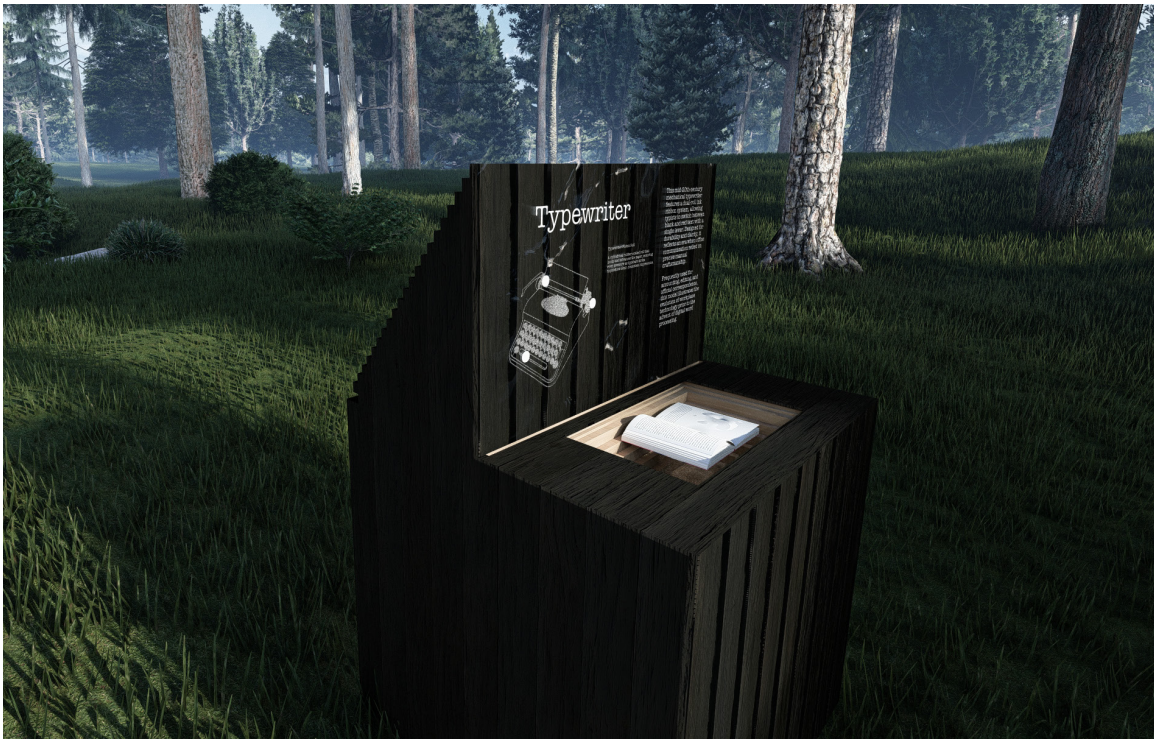


Figure 49. Render representing the reinterpretation of the exhibition case. Drawing by the author.

VI. CONCLUSIONS

Transparent wood, a new engineered bio-based composite, represents the culmination of a long journey where nature and technology converge to redefine the language of architecture, embodying both memory and innovation and offering a new chapter in the ongoing dialogue between tradition and scientific progress.

This thesis aimed at demonstrating how the intrinsic hierarchical structure of wood, its mechanical resilience, and thermal and optical properties, can be reinterpreted, or better, engineered, through scientific and technological processes to manufacture new materials. Transparent wood is the result of an accidental finding by S. Fink in 1992, where the only purpose of the study was to examine the internal structure of wood, and rediscovered two decades later when its great potential became evident to the scientific community. [39]

Although transparent wood is a promising multifunctional material, its durability under outdoor conditions remains one of the limiting factors for real-world implementation. Starting from samples preparation to laboratory test on the durability under UV radiation, it was possible to move a step toward the performance assessment. The research indicates transparent wood as a dynamic system in which both the wood scaffold and the polymer matrix contribute to the long-term performance, which can be improved by functionalization strategies, such as integrating UV absorbers.

The challenge for the architectural field is not only to adopt new materials but to interpret them, to translate technological achievements into spatial experiences. The architect must therefore act as a mediator between disciplines, stepping into the shoes of chemists, engineers, physicists, and so on, while maintain the vision that transforms matter into space. Transparent wood is a material that invites to rethink the relationship between interior and exterior, tradition and progress, permanence of structure and fluidity of light. The ultimate responsibility of the architect is to ensure that this innovation does not remain confined to laboratories but becomes part of the built environment. Transparent wood is thus more than a new material: it is a manifesto for a new architecture that embraces changes and incorporate them.

The culminating aim of this thesis is not only to highlight the scientific and technical qualities of transparent wood, but to affirm its architectural destiny. To fully understand wood's internal structure and performance characteristics, suitable for subsequent engineered products. To immerse in the science and technology of materials discipline in the preparation processes that transform natural wood into its transparent declination. To assess the new material's performance as a base for possible real-world applications. To imagine a new built environment made by luminous interiors where transparency and strength coexist. To give future and space to innovation.

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