Advanced Engineered Wood-Material Concepts

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Abstract

The variety of wood-based products is huge; some are produced and marketed in large volumes while others are for a very specific use and therefore also often only produced in small volumes. This chapter introduces a group of new materials, existing mainly only in laboratories or in production at pilot scale. These materials often go under the name *bioinspired materials and smart wood-based materials*. The second part of the chapter presents engineered wood products (EWPs) with other or additional functions than only the load-bearing capacity related not only to properties such as acoustic, heat transfer, light-weight, and extraordinary shape stability, but also to functions such as hybrid functions, improved possibility to form to a given shape, installation solutions, and esthetic and tactile performance. These materials are already on the market since many years and are in this chapter briefly introduced.

Keywords

Bioinspired materials · Smart wood-based materials · Hybrid wood elements · Thermal-insulation · Ski cores · Bilayer construction · Engineered wood products

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35.1 Overview

Wood can be utilized in many ways and in many shapes, without modifications or by applying additives to extend the life span of the material. To meet the structural demands of new construction, a range of derivative wood products, called engineered wood products (EWPs), are being manufactured by combining, e.g., sawn timber, veneers, and/or strands with adhesives or mechanical joints, as described in ▶ Chaps. 24, ▶ 25, ▶ 26, ▶ 27, ▶ 28, and ▶ 30 in this Handbook. In addition, timber can be combined with other materials to obtain new products with unusual performance profiles and new application potentials, with better overall properties than the starting constituents [1]. This field is wide and complex. Wood residuals, such as sawdust, shavings, and wood flour can, for example, be combined with thermoplastics, thermoset binders, or synthetic fibers, to produce a wood-plastic composite (WPC), a wood-fiber composite (WFC), or a fiberboard with higher flexibility than conventional boards. Another concept can be to join timber or an EWP with another common building material, such as concrete, steel, and glass.

This chapter gives an overview to not only different EWP concepts not dealt with in other chapters of this Handbook, but also totally new uses of wood that are under development. The chapter is divided into the following sections, describing the conceptual ideas of the products microscale to macroscale:

- Bioinspired materials and smart wood-based materials
- Multifunctional wood elements
- Engineered wood systems
- Complex and efficient geometries in timber construction

EWPs are now seen to be high-performance structural wood-based materials, construction elements manufactured by bonding together sawn timber, veneers, wood fiber, particles, or strands. This definition is strongly based on the decisions of the US Engineered Wood Association (APA) and its industrial members [2]. In a broader sense, any product of an engineering process with properties engineered for a specific use can be seen as an EWP, and currently there is a dynamic innovation process developing new engineered wood materials, elements, and products, ranging in length, from microstructures to large units. The growing timber-manufacturing industry is also facing challenges related to the increasing geometrical complexity of architectural design. Complex and structurally efficient curved geometries are nowadays easily designed, but their realization involved intensive manufacturing and excessive machining. This chapter deals with important EWPs which have not been covered in ▶ Chaps. 24, ▶ 25, ▶ 26, ▶ 27, ▶ 28, ▶ 29, and ▶ 30 by introducing examples of engineered wood products exceeding the traditional product concepts, i.e., products such as biologically inspired engineering (bionics), new wood-material concepts, hybrid wood-based components and EWPs, systems with specific functions, and complex and structurally efficient curved geometries in construction.

Thus, *engineered wood* describes wood products that are engineered for structural applications such as cross-laminated timber (CLT), glued-laminated timber (GLT or glulam), laminated strand lumber (LSL), laminated veneer lumber (LVL), oriented strand board (OSB), parallel strand lumber (PSL), structural plywood, and various types of box beams, I-joists, and other engineered speciality products [2, 3].

Publications and talks by Guss [4, 5] introduced the term "Engineered Wood Products" to wood experts, and Eldag [6] and Niemz [7] acquainted the German wood industry with this category of wood products. The books by Smulsky [8] and Williamson [9] set a clear agenda for the description of and design with EWPs, where the literature and current practical knowledge concerning the structural EWPs of that time were collected together providing a range of design values. With "APA – Engineered Wood Handbook" [9], a very comprehensive and concise compilation of the technical information associated with the design and use of EWPs was published, and Koponen and Kairi [10] provided a survey of the basic production concepts, material properties, and applications of EWPs such as LVL, PSL, and LSL. New handbooks, such as the CLT Handbooks [11, 12], complete the library of books describing EWPs. EWPs can now also be described in a wider context, where wood-based materials with not only structural properties are included, i.e., construction materials that are primarily of esthetic and tactile interest; see [13, 14].

The acronym EWP is thus a synergism of the true meanings of the single words:

- Engineered – the application of mathematics and the physical sciences to the needs of humanity and the development of technology
- Wood – essentially "wood-based" in this context
- Products – items produced by or resulting from a process in order to meet a specific requirement

In this chapter, the term "Engineered Wood Products" is extended to structural wood materials, as discussed above, and embraces the whole spectrum of wood materials engineering with respect to specific purposes and performances. It is however virtually impossible to summarize and compile the whole spectrum of engineered wood materials and products which are established on the market. Currently, there is an ongoing dynamic innovation process in the field of wood material and wood product engineering, and the broad spectrum of engineered wood materials and products is continuously expanding.

35.2 Bioinspired Materials and Smart Wood-Based Materials

Biologically inspired engineering or bionics is the application of biological methods and systems found in nature to the study and design of engineering systems and modern technology and is the base for bioinspired materials.

35.2.1 Bioinspired Materials

In recent years, biomimetic and bioinspiration have become an important focus in materials research and engineering. A bioinspired material may be defined as “a synthetic material whose structure, properties or function mimic those of a natural material or living matter.” In this context, bioinspiration is usually meant to go beyond the pure mimicking of the natural example and to capture the essence of certain functionalities, extract the basic principle behind them, and transfer them into new, sometimes very different materials and structures [15, 16]. This type of technology transfer has become increasingly popular with the advent of sophisticated investigation methods, revealing the astonishing inner structure of materials, and the availability of powerful computation that shows the elegance of solutions developed by a long period of evolution. In many cases, it is hoped to obtain new high-performance materials based on resource-efficient technologies or to find sustainable solutions for material problems. It is important to note that technological progress has made it possible nowadays to generate complex structures and to develop small features as they are found in nature.

Typically, structural materials used by nature consist of organic polymers or of polymers and ceramic particles [17], due to the limited availability of elements that organisms can glean from their environment and the limited range of substances they can synthesize from them. The limitations in chemical variety are, however, more than balanced by the enormous structural variation and the skillful combination of stiff and pliant components into composite materials. Most natural composite materials contain reinforcements in the size range of nanometers, often fibrous in nature, and arranged in an intriguing and optimized architecture to achieve favorable material properties and combinations, such as stiffness and toughness at the same time [17]. Examples include bone, teeth, seashells, and various plant tissues including wood [18–20].

It is therefore tempting to imitate the synthesis of biological materials, and several attempts have already been made [21–23], although their fabrication is still extremely challenging. Nature grows materials, structures, and whole organisms by self-assembly, which has been shown to be a suitable laboratory technology for small structures, but the scale-up of small structures into large-scale, load-bearing units is still a major problem. Another unsolved problem of technology transfer is the ability of biological materials to respond to biophysical stimuli. Biological materials can change during growth to optimize functionality and adapt to subsequent changes. Adaptability and the ability to self-repair would be very favorable also in many technical applications. In this respect, there is still a long path to travel, but on the way, there are valuable lessons to be learned and useful products to be exploited. In the following sections, there is an overview of particularly inspiring properties of wood and some milestone achievements.

35.2.2 Wood as a Source of Bioinspiration

Among the many intriguing biological organisms and structures, trees are a prime example of very large yet extremely light-weight constructions. They grow in a mechanically optimized manner and consist of a highly porous yet rigid material – wood. Wood has been used by mankind for many centuries for building, for furniture, and also for high-performance technical applications. The first airplanes were made from wood, because it is uniquely suitable for use in rigid and light-weight constructions [24]. The previous chapters in this handbook have already treated wood extensively as an extremely versatile material and as a raw material for sophisticated biobased products, but wood offers more: It represents an inspiring source of ideas for new light-weight, cellular, and sustainable materials with enhanced properties.

Hierarchical Structure

Like a number of biological tissues, wood follows the main principle found in nature. Instead of using a variety of basic components to create its physical properties, the focus is on building a complex and sophisticated structure with a minimum of constituents. In plants, a Young’s modulus range from 0.3 MPa to 30 GPa, and a compressive strength range from 0.3 MPa to more than 300 MPa (comparing parenchyma with the densest palm), is achieved by using only four basic building block substances: cellulose, hemicellulose, lignin, and pectins, as components [25]. These components can be present in varying amounts, which allows considerable adjustment. The main effect on the physical properties of trees is, however, achieved by mechanically optimized structures that span a large range of length scales (Fig. 35.1):

- The macroscopic scale: optimized shape of stem/branch
- The millimeter/submillimeter scale: variation in the volume fraction of different tissues (e.g., fibers, parenchyma; earlywood, latewood)

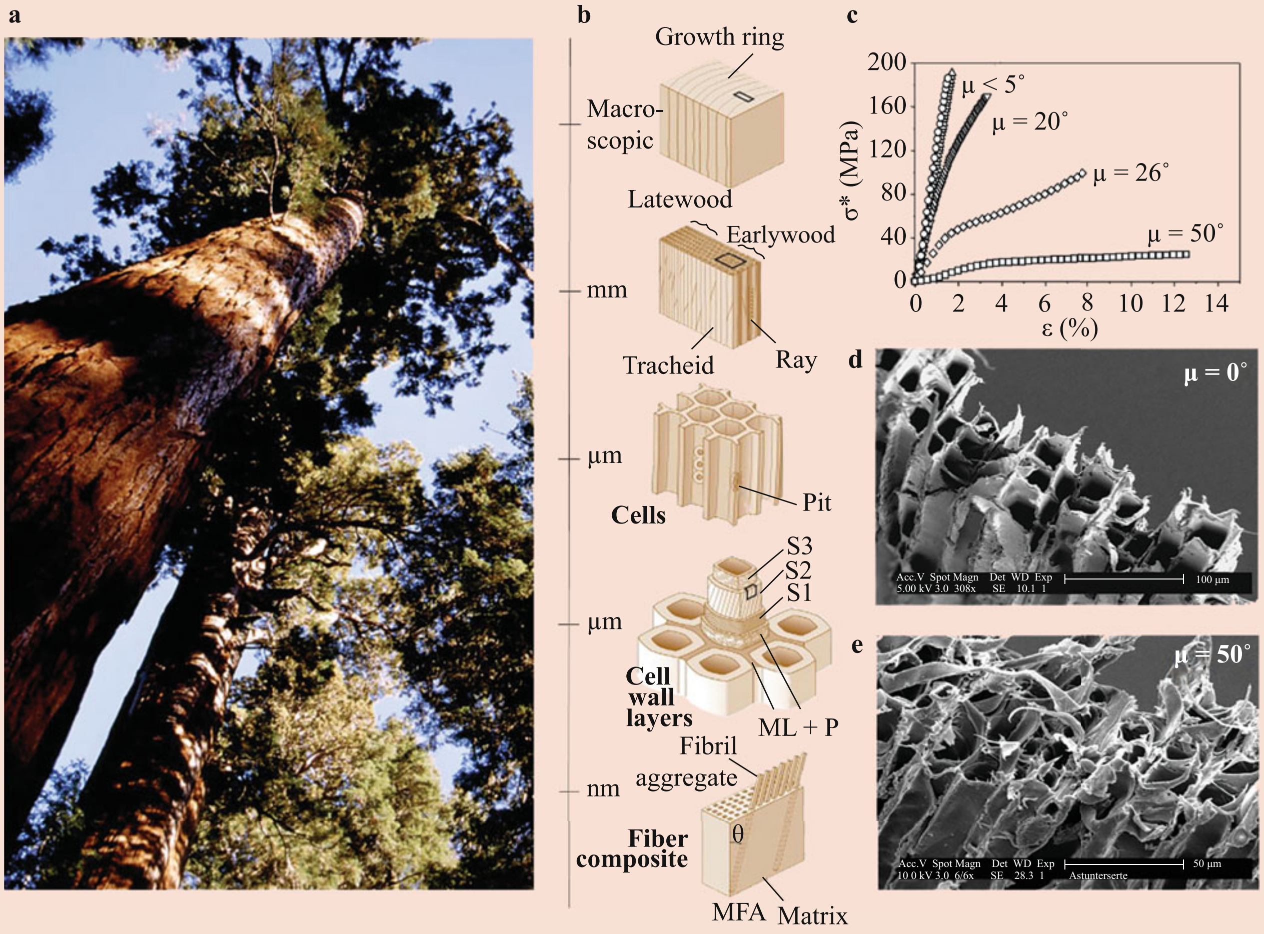


Fig. 35.1 Hiearchical structure of wood: (**a**) the tallest trees *Sequoia sempervirens* (Photo H. Lichtenegger), (**b**) levels of hierarchy from the macroscopic to the nanometer scale (Adapted from [26] with permission), (**c**) macroscopic tensile properties of Norway spruce as a function of cellulose microfibril angle (MFA) in the S2-layer (Reproduced with permission from [27]), (**d**) and (**e**) different fracture surfaces of Norway spruce fractured under tension. Normal stem wood with very low MFA fractures in an almost brittle manner, while compression wood with large MFA shows a complex fracture surface and thus high-fracture energy. (Reproduced with permission from [28])

- The micrometer scale: cellular structures with different anatomies and densities
- Nanometer scale: variations in the orientation of the cellulose microfibrils within different layers in the plant cell wall

On the macroscopic scale, the outer shapes of trees and branches have been the subject of many studies, and bioinspired shapes of branching structures have been derived. The construction level is however not the topic of the current section, and the reader is referred to the works of, e.g., Mattheck [29]. The hierarchical structure of wood has been described in many textbooks and review articles [17, 25, 30]. Here, only the main points will be briefly reviewed.

In wood as a material, typical structural length scales vary from several millimeters down to approximately 1 nm. On the millimeter scale, different tissue types are arranged in zones, such as earlywood and latewood zones or as vascular bundles in palms. On the micrometer level, wood can be described as a porous material consisting of hollow tubes roughly 10–60 μm in diameter with a circular or rectangular cross section – the wood cell. They are aligned more or less parallel to the stem or branch and result in high stiffness in the longitudinal direction and lower stiffness in the transverse directions. Wood has been modeled as a honeycomb structure by, e.g., Gibson and Ashby [25, 31, 32]. The Young's modulus and strength along the grain depend linearly on the relative density ρ^*/ρ_s, where ρ^* is the density of the honeycomb structure and ρ_s is the density of the honeycomb cell wall, while dependences on $(\rho^*/\rho_s)^3$ and $(\rho^*/\rho_s)^3$ are found for stiffness and strength, respectively, transverse to the fiber-longitudinal axis. Structural variation is achieved by variations in cell shape, such as circular cells in compression wood and fibers of deciduous trees and roughly rectangular or hexagonal cells in softwoods (tracheids). The density of the wood is directly related to the ratio of cell-wall thickness to cell diameter, which means that the overall density is dependent on the ratio of thin-walled earlywood to thick-walled latewood.

The wood cell wall is an impressive example of an optimized and mechanically customized nanocomposite. It consists of layers of nano-sized cellulose fibrils embedded in a hemicelluloses/lignin matrix, the cellulose fibrils being wound around the tube-shaped wood cell in a spiral fashion. A detailed description of the structure can be found in the textbook by Fengel and Wegener [33]. The mechanically most important layer is the secondary wall (S2) which contains strictly parallel fibrils that are slightly tilted with respect to the longitudinal cell axis by an angle usually referred to as the microfibril angle (MFA).

It has been shown in a number of studies that the orientation of the cellulose fibrils in the wood cell wall can vary considerably within a single tree: Large angles are found mainly in the inner part of the stem close to the pith or in conifer branches, whereas small angles are found in the outer regions [34]. It is widely recognized that variations in the MFA can lead to large differences in mechanical properties [20, 35–38]. In Norway spruce, it has been observed that a change in the MFA from 0° to 50° leads to a decrease in stiffness and strength by roughly an order of magnitude, while the extensibility increases by an order of magnitude [27, 28]. The MFA can therefore be regarded as a powerful means for mechanical adaptation in trees [34], so that a growing tree can build material that is optimized to withstand specific loading patterns such as the bending of branches or compressive forces within a stem [39]. The structural optimization also allows adaptation to functional requirements that may change during the lifetime of the tree, within the range of possibilities available to trees, i.e., material can only be added, not exchanged.

Optimized Performance and Functionality

Due to its low density, sophisticated cell morphology, and cell-wall architecture, wood is a material offering high-mechanical stability, flexibility, and low weight. It has been shown that for an ideal material, maximizing the ratio of Young's modulus to the square of the density, MOE/ρ^2, is suitable to minimize the risk of failure by elastic buckling for columns under compression [40]. While a tree stem is an inhomogeneous body with variable E and ρ, this consideration sheds light on possible optimization strategies. In this context, low density is a great advantage and balsa wood loaded along the fiber direction represents an optimum value of MOE/ρ^2 [32]. At the same time, wood is remarkably tough and failure tolerant. Stanzl-Tschegg [41] have identified several mechanisms that retard crack-growth mechanisms:

- A cell structure containing holes that may act like crack stoppers
- Fibers used as reinforcements cause crack deviation and crack branching
- The wood cell wall consists of layers with different toughness values and different load-bearing capacities, which may lead to crack deviation, retardation, and even arrest
- Fiber bridging, i.e., fibers which are stronger than the surrounding matrix, keeps already broken parts together

One key feature of the high toughness of wood is the behavior of the wood cell wall under large deformations, which has been the topic of several studies [42, 43]. It has been suggested that the load-bearing cellulose fibers carry the load mainly without deformation, while the hemicelluloses/lignin matrix is deformed mainly by shear [44], so that stiffness and toughness can be achieved simultaneously. On the molecular scale, this requires tight binding of the cellulose fibrils to the matrix while still allowing plastic deformability. Keckes et al. [45] found that large cell-wall deformations were associated with what the authors termed a "stick-slip mechanism." When the wood cell wall was strained beyond its yield point, an irreversible elongation was observed, but when the stress was released, the cell wall apparently regained its stiffness, judging from the mechanical response to the next deformation cycle. The authors concluded that molecular bonds in the matrix were broken during deformation but that nonspecific bonds in the matrix reformed immediately, so that the cell was arrested in its new elongated state, resembling the mechanism of Velcro on a molecular scale [45].

In addition to the remarkable performance of wood as a material, trees also possess powerful means of movement. This is often not perceived as such, because the movement is slow, e.g., the bending of branches toward the light or the bending upward of leaning stems. This is achieved by the formation of so-called reaction wood in branches and leaning stems to counterbalance bending moments, which is actually able to move a stem into an upright position. In conifers, a push-up effect is achieved by building so-called compression wood on the lower side of the branch or leaning stem [46]. In deciduous trees, a cellulose-rich and swellable layer (gelatine layer, G-layer) is incorporated in the wood cell wall. It contains cellulose fibrils strictly oriented along the cell axis and is believed to play an important role in withstanding high-tensile stresses [47, 48], and the orientation of cellulose microfibrils in the wood cell wall also plays an important role in plant motion.

Principles Worth Mimicking

There are thus a number of principles that make wood an attractive source of bioinspiration. Some of them may be used to obtain materials with properties superior to those of wood for a certain application or to achieve similar properties based on different constituents. The latter may, for example, be useful for use in high temperatures, where polymer-based materials would not provide the required heat resistance. It is also conceivable to add functionality (e.g., magnetic, optic) to wood-like materials, while keeping the benefit of a stable light-weight material. It should also be noticed that not all the characteristics of wood may be desirable. For example, the inherent anisotropy of wood may be either a benefit or a curse, depending on the application. If it can be used in a tailored way, it could be great benefit to make a material that is particularly suitable for a predefined loading direction or even to exploit anisotropic material parameters such as directional differences in swelling for enhanced functionality. In the following, a list of attractive principles is given, without claim for completeness:

- Optimized light-weight structure
- Large variety of properties with minimum variation of material
- Designed anisotropy for special loading cases
- Mechanical and structural optimization
- Adaptive by the addition of material with a desired structure
- Multifunctionality (water conduction, mechanical support)
- Special combination of mechanical properties, very high-fracture toughness
- Self-assembly of fibers in preferred orientation
- Passive actuation

These advantages come, however, at a cost, namely the complex and hierarchical structure of wood. Directly producing and assembling such complex materials in the laboratory is a great and still unmet challenge, and various approaches reported in the literature concentrate on imitating at least certain aspects of wood. In the following sections, an overview of recent research is given.

35.2.3 Wood Modification and Wood Templating

Despite the recent progress in nanofabrication and self-assembly of nanomaterials in the laboratory, it is still enormously challenging to build large structures with nano- and microstructural features across multiple length scales. One of the main limitations in the design of synthetic materials nowadays is the task of developing small-scale features into large, macroscopically functioning materials, which means that it is tempting to use preexisting biological scaffolds as templates for new materials (cf. wood modification in ▶ Chap. 16). Wood is particularly suitable for this purpose since it has a cellular structure that allows infiltration by solutions and reagents and since its polymeric nature allows modification or template removal by raising the temperature.

A variety of approaches have been reported in the literature. An excellent review has been given by Burgert et al. [49]. In most of the studies cited, the aim has been to keep the cellular structure and inherent directionality of wood and to modify the cell wall with polymers or minerals to achieve new properties and new functionalities. The wood anatomy means that wood can, for instance, be functionalized to act as a separation membrane or as a wood scaffold of high microporosity where the large-diameter lumens offer an ideal support for filtration technologies.

Modification can be achieved by introducing polymers in the cell wall, at the interface between lumen and cell wall, or in the lumen. The grafting of polymer chains onto the cell wall can be used to achieve a hydrophobic effect [50, 51], and new functionalities can be achieved, e.g., by introducing conductive polymers such as polyaniline into the wood structure [52, 53]. Such materials can be an interesting substitute for synthetic electronic support, showing also an increased flame retardance [49].

Another approach is to introduce inorganic material into the wood structure to achieve organic/inorganic hybrid materials with new functionalities. For example, wood has been used as a scaffold for the assembly of colloidal iron oxide particles [54, 55]. The iron salts were not precipitated directly in cell wall; instead a thin layer of magnetic particles was formed on the cell-wall surface inside the lumen, and due to the inherent spatial directionality of the wood architecture, magnetic anisotropy and a direction-dependent hysteresis loop were also obtained. In a magnetic field, the magnetic wood blocks could be lifted or flipped [55]. Such materials are promising for use in magnetic switches or other magnetically actuated elements.

Inorganic matter can also be deposited directly in the cell wall, a process inspired by biomineralization, where an organic matrix acts as a template for the controlled formation of very small (typically nano-sized) mineral particles. In the case of plant cell walls, naturally occurring biominerals are mainly calcium oxalate, calcium carbonate, and silica [56]. Silica particles are known to be a deterrent for herbivores and are, for example, present in rice and equisetum, where they cover the epidermal surface with knob-like structures [57]. In wood technology, silicon compounds have a long-standing tradition of use for preservation. Depending on the substance and the infiltration method, filling of the lumen or cell wall penetration can be achieved, and the cell wall can be successfully modified using tetraalkoxysilanes as sol-gel precursors, particularly when hydrolysis and condensation are controlled so that the reactions take place within the cell wall. Organic/inorganic hybrid materials can thus be achieved. A comprehensive overview of the use of inorganic and organic silicon compounds in wood modification is given by, e.g., Mai and Militz [58, 59].

A much greater variety of biominerals can be found in the animal kingdom. Calcium minerals are the most common calcium carbonate being found in egg shells and crustaceans, being very popular in marine mollusks. Calcium carbonate can also be introduced into the wood cell wall in a bioinspired process, as described in [60], where mineralization was achieved by synthesizing amorphous calcium carbonate as a transient phase, dimethyl carbonate being hydrolyzed in situ in the presence of calcium ions. Mass gains of up to 20% were achieved, and the calcium mineral was formed mainly found inside the cell walls. Interestingly, a flame retardancy effect was also achieved.

All the materials described above still contain wood as a basic material, but the natural wood tissue can also be exploited as a blueprint for materials of an entirely different chemical nature, providing only the architecture of the final material. Usually, the aim is to obtain inorganic structures (ceramics) that faithfully replicate the structure of the wood, but exhibit higher strength, higher temperature resistance, or greater chemical inertness than the natural material. A number of literature studies report, for example, single and mixed oxides [61–63], carbides [64], and oxycarbides [65].

For processing, essentially two avenues can be followed [66] as shown in Fig. 35.2. The first is the application of reactive templating to turn the organic wood structure into an inorganic compound. In this way, both the macro- and microstructure of wood have been replicated in carbide ceramics. Pioneering work in this field was carried out by Byrne and Nagle, and by Greil and Lifka [67, 68]. Since then, the production of biomorphic ceramics by wood templating has become a rich research field. The procedure typically involves wood pyrolysis (above 500 °C) to turn the wood into a carbon material while preserving its porous structure, followed by infiltration with liquid melt or metal vapor above 1200 °C, depending on the desired material. For example, SiC, TiC, or Si/SiC ceramics can be achieved in this way [64, 66].

Alternatively, templating can be achieved by substitution, in which case an inorganic phase is formed inside the wood structure following careful (usually vacuum-assisted) infiltration of either wood or a carbonized wood scaffold. In this approach, wood is used as a template and is then finally removed, usually by oxidation at a temperature above 500 °C. In order to obtain a solid structure, a precursor solution is needed that is capable of forming solid inorganic material in the presence of the template. Metal salt solutions or sol-gel precursors are suitable. Infiltration is typically performed after purification with water or organic solvents to remove low-molecular-weight components that might react with the infiltrated compound [49]. The liquid phase is then solidified by curing or by a sol-gel process, yielding an organic/inorganic hybrid material, the organic phase of which can subsequently be optionally removed by oxidation. A variety of metal oxides with the morphology of wood can thus be obtained (Fig. 35.3). Examples include silica, titania, zirconia, and zinc oxide [66, 69]. Recently, replication of the hierarchical structure of wood has also been achieved in magnesium oxide and magnesium silicate [70]. Using salt solutions for infiltration, other nonoxide materials with enhanced functionality, can be fabricated, such as BaFBr doped with Eu2+. Such materials can be used for storage and for the display of X-ray signals, for example, in image plates [71].

All the above approaches have been shown to be more or less suitable for the faithful transfer of the cellular microstructure of wood, but only a few studies have been successful in replicating the nanostructure of the wood. The greatest challenge in this respect is the limited accessibility of the essentially dense cell wall, which means that cell-wall

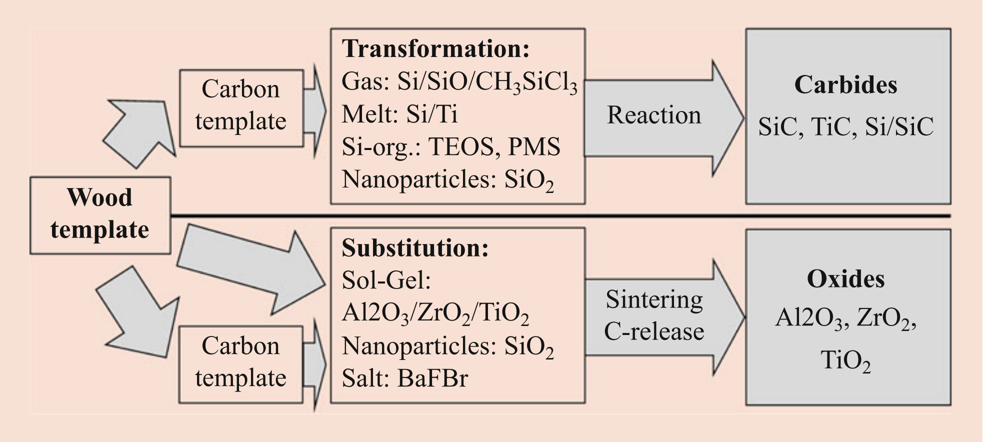


Fig. 35.2 Processing schemes for the conversion of wood into structural ceramics and composites, with examples of achievable materials. (Redrawn and adapted from [66])

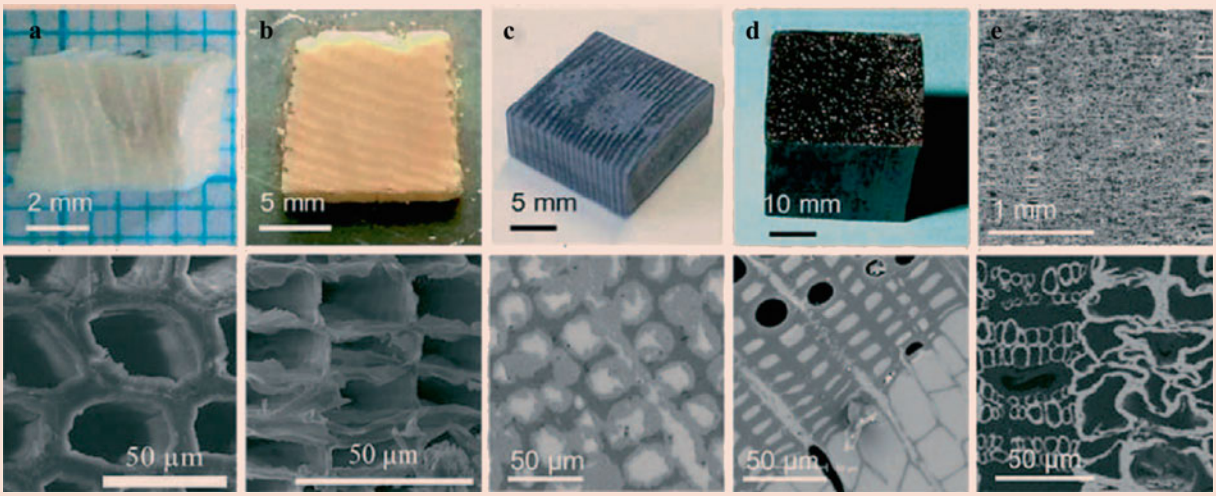


Fig. 35.3 Photographs and scanning electron micrographs of softwood-derived inorganic nonmetallic materials: (**a**) silica, (**b**) yttria, (**c**) silicon-silicon carbide, (**d**) silicon oxycarbide, and (**e**) barium fluorobromide. (Reproduced with permission from [49])

infiltration usually requires the preliminary oxidative or chemical removal of the lignin [72]. Alternatively, the cell wall can be swollen with a surfactant [73], or both these strategies can be combined. Candidates for infiltration must be low molecular weight compounds to ensure sufficient penetration. The first successful study yielding the faithful replication of the nano-scale structure of wood was performed with cerium oxide/zinc oxide ($Ce_{0.5}Zr_{0.5}O_2$), as shown in Fig. 35.4 [74]. The removal of the template turned the original cellulose microfibrils into nanosized cylindrical pores, the orientation of which was well preserved, as demonstrated by small-angle X-ray scattering. Normal wood showed the typical signal corresponding to a small microfibril angle, whereas compression wood exhibited the signal for a large microfibril angle like that in the original raw material. The process was later adapted to form hierarchically structured silica wood replicas. The wood cell wall was infiltrated using the sol-gel precursor tetraethoxysilane TEOS followed by calcination at an elevated temperature to remove the cellulose [72, 75].

Wood modification and bioinspired wood templating thus yield a variety of new materials with enhanced mechanical properties, such as greater strength due to inorganic components, and also greater toughness than solid ceramics due to the microporosity. Additional functionalities such as electrical conductance, magnetic properties and optical phenomena such as luminescence, can also be achieved. The above approaches have a high-technological potential due to their versatility, the readily available raw material, and the inherent possibility of performing nano-scale modifications to obtain large-scale products for macroscopic applications.

35.2.4 Wood-Inspired Structures

The use of wood as scaffold and as a blueprint for new materials has already been very successful, but synthetically imitating the structure of wood is still extremely challenging and can be regarded as the “holy grail” of biomimetics. A synthetic replica of wood would have to reproduce the cellular architecture of wood, the layered structure of the cell wall, and the spiral orientation of the nano-sized cellulose fibrils around the wood cell wall. Nevertheless, several researchers have attempted to extract the architectural principles of at least one hierarchical structure level of wood and to implement them into novel materials and structures.

Aligned Cellular Structures and Foams

It can be seen in the light microscope that wood is a porous, cellular structure that can, to first approximation, be compared with a foam. Foam-like materials are of great importance in light-weight applications and they have been produced from various basic materials ranging from polymers to ceramics and metals. Although technologically important, not all types of foam can be or should be regarded as bioinspired. The special features of the cellular structure of wood are certainly the controlled size and shape of the wood cells, the interconnectivity of the cells via pits, and the anisotropic architecture, but although the anisotropic architecture is essential in the living tree for mechanical support and water and nutrient conduction, it may not always be desired in technical applications. In particular, for construction purposes isotropic materials are usually preferred. There are, however, a number of applications where aligned pores are

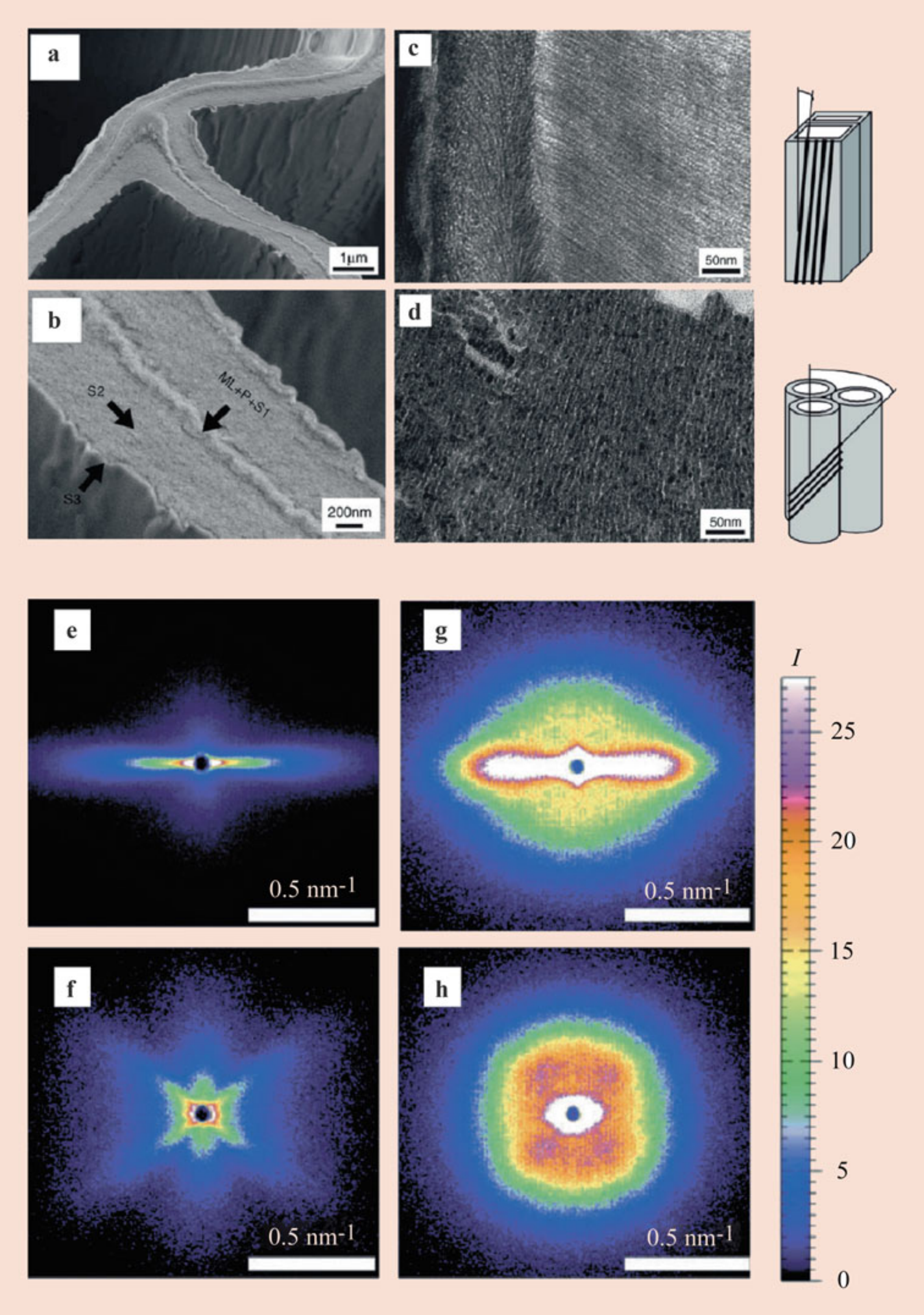


Fig. 35.4 Hierarchically structured $Ce_{0.5}Zr_{0.5}O_2$ monoliths fabricated by substitution templating: (**a**) and (**b**) SEM images at different magnifications. The interfaces between different wood cell-wall layers are clearly visible in the cross section, (**c**) a TEM image of impregnated and dried compression wood, and (**d**) a TEM image of the calcined sample. A clear fibrillary structure and preferred nanoparticle alignment is seen on the nanometer scale in both cases, (**e**) and (**f**) 2D SAXS patterns from macerated wood under moist conditions, and (**g**) and (**h**) SAXS patterns from $Ce_{0.5}Zr_{0.5}O_2$-templated wood after calcination (**b**, **d**). (Reprinted with permission from [74])

of great interest, such as microfluidics, molecular filtration, and tissue engineering (e.g., to promote the directional growth of biological cells or to achieve materials that mimic the natural properties of, for example, bone) [76]. It is also conceivable to use directional porous materials for lightweight construction applications if the directionality can be tailored to fit the directions which are subjected to the principal load.

A variety of methods exist to introduce cavities into a matrix, the simplest being the addition of fillers (either hollow fillers or solid fillers that can be removed in the end) or the creation of bubbles from blowing agents such as CO_2 [77, 78]. Other methods are by etching or emulsion processing [79, 80]. The majority of these methods yield round, randomly shaped and randomly dispersed pores that bear no resemblance to wood cells. Directional pores can however be achieved by the use of a temperature gradient. Elongated pores have, for example, been introduced into metal by mold casting or zone melting [81]. A popular technique for creating elongated pores and directional composite structures is freeze casting [82, 83], which is used to produce ceramic, polymer, or organic/inorganic hybrid foams. In this approach, an aqueous suspension of small particles, an aqueous solution of sol-gel precursors, or a water-soluble polymer is placed on a cooling plate and freezing is initiated by the application of a pronounced temperature gradient (Fig. 35.5). During freezing, the formation of ice causes the displacement and agglomeration of the additive in any remaining liquid pockets. Solidification of the additive may occur by close packing of particles, sol-gel formation, or polymer cross-linking, depending on the system used. The ice is subsequently removed by sublimation. A further sintering step may follow in the case of ceramics.

In this way, a great variety of directional porous scaffolds have been obtained. For example, natural polymers such as gelatine have been used to yield structures that visually resembled wood cells and could be used for the culture of cartilage cells [86]. Other authors have reported the use of poly(vinyl alcohol) (PVA) to obtain differently shaped anisotropic porous polymer structures or hybrid PVA-silica composites with anisotropic strength [76]. Polymer scaffolds can also conveniently be converted into ceramics [79] by conversion processes that include reactive templating or substitution templating, as described above for wood as a scaffold. For example, SiO_2/SiC monoliths have been made from polysiloxane and rice-husk-derived silica via freeze casting and subsequent sintering [87]. Ceramic scaffolds with aligned pores can also be conveniently fabricated directly from ceramic slurries. A wood-like structure has, for example, been obtained by freeze casting and self-assembly of 500 nm alumina platelets together with smaller colloidal silica particles, giving a thin-walled honeycomb structure with an average cell diameter of approximately 30 μm [88] (Fig. 35.6a). The addition of colloidal silica was shown to greatly improve the mechanical properties of the structure by filling the voids between the platelets and acting like a matrix. In all these studies, anisotropic materials with wood-like elongated macropores were fabricated with just water ice as porogenic template. Such an approach is essentially facile, inexpensive, and environmentally benign. Due to its versatility, it offers the possibility to simultaneously process nanoparticles, polymers, and biomolecules [76], and it opens up the way to the implementation of nanofibers in the cell walls.

In wood, the physical properties are strongly determined by the nature of the nanofiber composite in the cell wall. Introducing nanofibers into the cell walls of materials with a directional porosity is therefore a major step toward mimicking the hierarchical structure of their natural counterpart. Various nanometer-sized fibers can be used for this purpose. Directional foams have been prepared from MFC (microfibrillated) nanofiber suspensions in a freeze-casting approach [89] (Fig. 35.6b, c). They showed a high toughness,

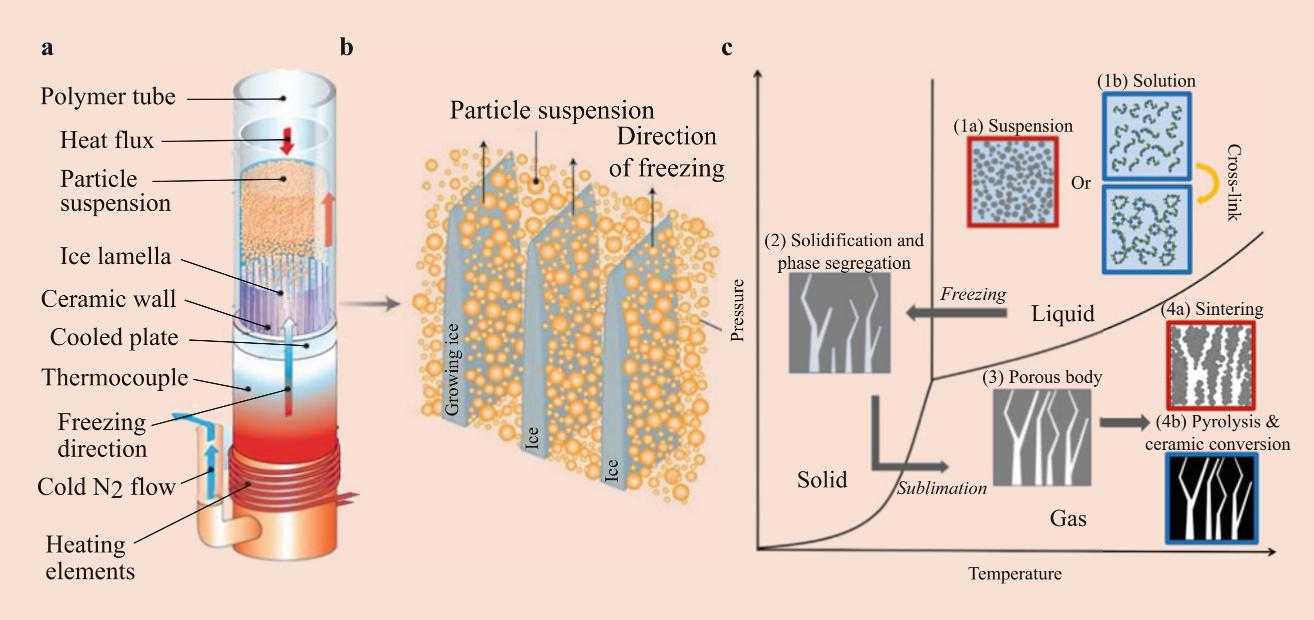


Fig. 35.5 The principles of freeze casting: (**a**) diagram of a freeze casting setup. An aqueous suspension containing particles or sol-gel precursors is placed on a cooled plate from which ice crystal formation starts, (**b**) during ice formation, the impurities are excluded from the water and selectively agglomerated in pockets between the ice lamellae. Different morphologies can be achieved by adapting the composition of the suspension and by tuning the process parameters (Reproduced with permission from [84]), and (**c**) schematic of the freeze-casting process and various processing routes. (Reproduced with permission from [85])

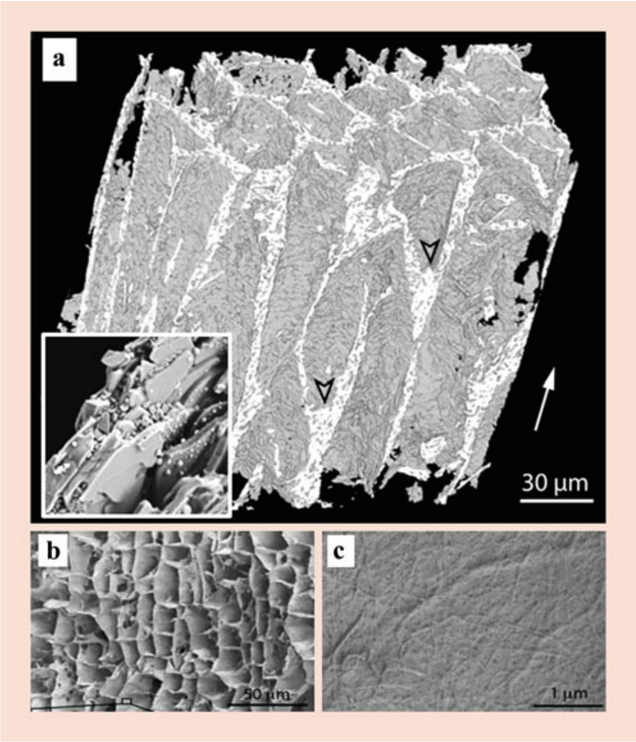


Fig. 35.6 (**a**) Example of a porous structure with a morphology similar to that of wood cells, but purely inorganic (made from alumina platelets and containing approx. 10 vol% of glassy phase, derived from freeze casting). The white arrow indicates the direction of olidification of the structure. The large image shows a 3D image from computed tomography (CT), and the inset shows the arrangement of alumina platelets (Reproduced with permission from [88]), (**b**) wood cell-shaped ultra-high porosity foam prepared from cellulose I nanofiber suspensions by freeze-drying, and (**c**) detail from the "cell wall" of foam in (**a**) showing the cellulose fibrils. (Reproduced with permission from [89])

which is remarkable since brittleness is particularly critical in stiff and highly porous materials. By adding xyloglucan, inspired by natural plant cell walls, the authors achieved a further increase in stiffness and strength. Freeze casting has also been used to prepare honeycomb structures reinforced by nanocellulose combined with layered silicates [90]. Ice templating of suspensions of cellulose nanofibers, graphene oxide, and sepiolite nanorods resulted in superinsulating, fire-retardant, and mechanically strong anisotropic foams [91].

It can be concluded, that by adapting the process parameters and choosing a favorable material combination, functionalities different from and in many aspects even beyond those of wood can be obtained. The foam and fiber-reinforced foam approach, in particular, is very promising, particularly in view of their relatively facile preparation. Nevertheless, it must be stated that it is difficult to control the orientation of the nanofibers reinforcing the cell wall. Since the fiber orientation has an immense influence on the properties of a composite, this is one of the key issues in wood biomimetics.

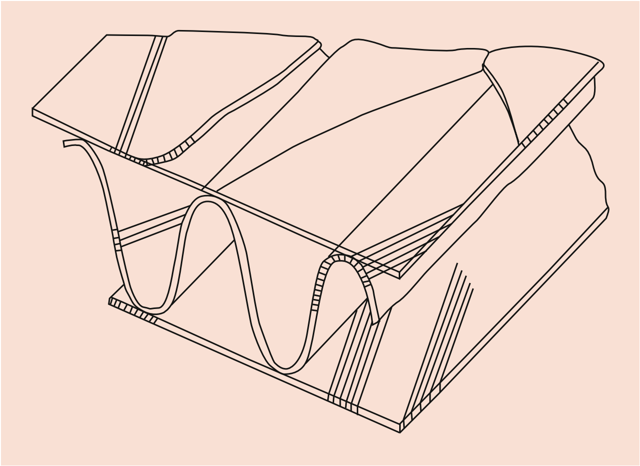


Fig. 35.7 Simplified cell-wall analogue produced from uniaxial glass. fiber prepreg. (Reprinted with permission from [93])

Macroscopic Cell-Wall Analogues

It is much easier to control the fiber orientation on the macroscopic scale than in the nanometer range. The fiber arrangement can be tuned through conventional fiber layup, weaving, or winding techniques, and some authors have sought to mimic the arrangement of the cellulose microfibrils in the wood cell wall. In an early study, Gordon and Jeronimidis [92] developed a composite material consisting of an epoxy matrix reinforced with hollow tubes of spirally wound glass fibers, and they found that the work of fracture depended greatly on the winding angle with an optimum at 15°, which gave the best compromise between loss of stiffness and strength and increase of fracture toughness. They also tested a combination of wound macrofibers and unidirectional glass fibers to achieve an increase in strength while maintaining high toughness.

In an attempt to design a structure that would lend itself more readily to mass production, these authors devised a corrugated cell-wall analogue [93] consisting of sheets of uniaxial glass-fiber prepreg that were folded to produce a corrugated structure as shown in Fig. 35.7. The fibers are arranged at about 15° to the long gaps between the corrugations producing a structure like the spiral windings in the wood cell wall. This material was developed to provide protection against explosives and against knives and bullets. It performed less well than the composite with wound macrofibers but was much easier to handle.

Although upscaling provides a very useful and convenient way to obtain deeper insight into biological phenomena, it has serious limitations. In composites, the size of the reinforcing components is of great importance, and nanocomposites may show properties quite different from those of composites containing macroscopic or micrometer-sized reinforcements. For example, particle reinforced plastics may show a much greater ductility when reinforced with nano-sized than with micrometer-sized particles [94]. This can be attributed to the increasingly important role of the interface between reinforcement and matrix as the particles become smaller. Working with nanofibers is however technically very challenging, and manipulating their orientation on the nanoscale is another complication not easily overcome.

Additive Manufacturing of Wood-Inspired, Hierarchical Nanocomposites

In recent years, additive manufacturing has become immensely important for the production of complex parts and structures. Seemingly endless opportunities exist both for large items and for material substructures down to the micrometer and even nanometer scale. Methods are typically based on photopolymerizable resins (e.g., digital light processing and stereo-lithography), the extrusion of thermoplastic materials (e.g., fused deposition modeling), or the solidification of ceramic powder via laser (selective laser sintering). A method of very high resolution can be achieved that may reach down to the nanometer range (multiphoton lithography [22]), and composite materials can be printed using inks filled with particles, small platelets, or short fibers. Direct ink writing is a suitable method, because it delivers material through a syringe nozzle in the form of a continuous viscoelastic filament that need not solidify immediately. It is essential to have the correct rheological properties to ensure flow and to obtain structures that withstand gravity and distortion. The orientation of anisotropic fillers can be controlled to a certain extent. The preferred orientation can be achieved via shear when the fiber-filled ink is pressed through a small nozzle. Magnetic fields and magnetic fillers have also been used. An excellent overview has been given by Studart [95].

Cellular structures mimicking balsa wood have been printed using the direct write technique with shear alignment of the fibrous filler. Compton and Lewis [96] used an epoxy resin filled with nanoclay platelets as a base ink, and SiC whiskers with submicron thickness and C fibers with a thickness of 10 μm were used as additional fillers. Triangular honeycomb structures with a cell size of approximately 2 mm were printed using a small printing nozzle which served as an alignment device for shearing the fibers during the printing process. Mechanical tensile tests on bars containing SiC whiskers and C fibers and loaded in the fiber direction gave a Young's modulus similar to that of the wood cell wall. The overall strength of the porous structure was similar to that of balsa wood, but the density was higher. Malek et al. [97] added short carbon fibers to an epoxy resin as a filler (Fig. 35.8). Using a relatively high-volume content of fibers (13%), they printed cellular hexagonal honeycomb structures inspired by balsa fibers and rectangular lattices inspired by balsa rays and combined experimental mechanical tests with model calculations. Due to limitations in the printing process, it was unfortunately only possible to orient the carbon fibers along the printed struts, i.e., perpendicular to the longitudinal cell axis. As expected, the Young's modulus in the plane was very high and exceeded that of balsa wood. Malek et al.'s calculations showed that the material would exhibit the same specific modulus out of the plane (along the longitudinal cell axis), if the carbon fibers could be oriented in this direction. It can be concluded that

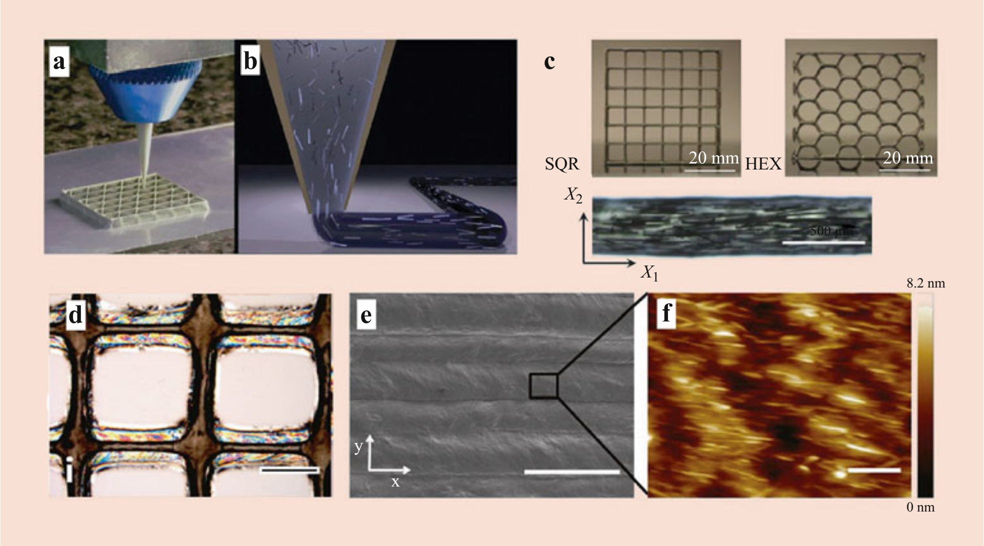


Fig. 35.8 Printing composites with short nanofibers: (**a**) direct printing of a triangular honeycomb structure composed of epoxy resin filled with SiC whiskers or with SiC whiskers combined with short carbon fibers (Reprinted with permission from [96]), (**b**) and (**c**) in a similar approach, rectangular and hexagonal structures were printed from short-carbon-fiber-reinforced epoxy resin (Reprinted with permission from [97]), (**d**) cellulose nanocrystals (CNC) in aqueous suspension were used to print square cells, (**e**) SEM image of printing filament, and (**f**) CNC aligned by shear along the printing direction shown by AFM. (Reproduced with permission from [98])

although the fiber orientation was in the "wrong" direction, the study was an impressive example of a cellular structure for which the properties depend on the direction of the micrometer-sized carbon fibers reinforcing the cell walls. Recently, shear aligned cellulose nanocrystals (CNC) have been used as reinforcement in 3D-printed cellular structures using viscoelastic aqueous and monomer-based CNC inks [98]. The preferential alignment of the CNC along the printed filaments was confirmed using AFM and XRD. The stiffness and strength were higher in the longitudinal direction, and further promising developments can be expected.

Nevertheless, a number of challenges remain. In all the studies mentioned, the cell size and cell-wall thickness were still larger than those in wood, because of the limited resolution of the direct writing process given by the diameter of the printing filament. Furthermore, and probably most importantly, the adjustment of the fiber orientation is still limited to the filament direction and – due to the layer-by-layer process – also within the printing plane. This condition is in principle similar to the restrictions encountered during the formation of cellulose fibrils in the wood cell wall that are also added layer-by-layer, starting from the middle lamella, but with the important difference that the cellulose fibers are formed locally by self-assembly and within each newly formed wood cell. Further advancements in the techniques of additive manufacturing will certainly allow more complex fiber orientation, potentially combining large-scale alignment methods such as external fields with local alignment techniques through shear and/or directed self-assembly.

35.2.5 Smart Wood-Based Materials

The twenty-first century is called the "Era of smart (intelligent) materials." At the beginning of the 1990s, this strange combination of words first appeared at scientific conferences [99–101]. Historical experience shows that the need to create new concepts in any branch of science is related to the needy to solve more complicated fundamentally new problems and is based on achievements in advanced technical industries. In this case, developments in the field of artificial intelligence revealed that it was possible to create a material that performs "intellectual" functions that were previously intended for software and electronic circuits. Synthesis and analysis of efforts and achievements in the fields of aeronautics, space, nuclear energetics, and medicine led to the concept of a new "smart" material, and this became the basis for the development of a new class of materials. There are various definitions of this term, classifications, directions of development of smart materials, and considerable research in this area [99–124].

The above examples are all concerned with imitating wood as a structure, but this section is dedicated to its functionality as a possible actuation system. Although plants are usually regarded as rather static systems, they exhibit a remarkable ability to move. In trees, this includes the bending of leaning tree stems to an upright position, the orientation of branches in relation to the sunlight, or the movement of the scales of pine cones. The mechanisms behind the movement in plants are unequal growth such as the preferential addition of material at certain sites, changes in the pressure in the cell (turgor pressure), and the swelling or shrinking of cell walls with changing humidity. The first two possibilities require living tissue, but the third is a passive mechanism that can also occur in dead tissue. It relies on predetermined changes when the environment changes and needs no control mechanism. Since hygroscopic materials harvest energy directly from the ambient humidity, it is not necessary to supply energy, and such types of motion are therefore particularly interesting for biomimetic transfer into technical applications [125–127]. Further advantages of hydraulic actuation include large motion amplitudes and the possibility to exert large forces, and it is important that hygroscopic swelling and shrinking are reversible offering repeated actuation, albeit on a relatively short timescale.

Smart Materials

Currently, the term "Smart materials" means intelligent or responsive materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields, light, or chemical compounds [113, 114]. Smart materials include shape memory materials [105, 108, 116, 123, 124].

Although many effects associated with smart materials were discovered a long time ago, the development of smart materials started a new phase in materials science, and smart materials now are the basis of many applications, including sensors and actuators, in different fields.

A concept of intelligent materials and a schematic representation of intelligent materials were first described by Takagi [99]. Classifications and characterizations of smart materials have been presented in many research reports [99, 100, 112]. Intelligence inherent in materials suggested by Gandhi and Thompson [100] is shown in Fig. 35.9, and the concept of an intelligent material is presented in Fig. 35.10 [109].

Whether it is a molecule, a material, a composite, an assembly, or a system, a "smart material and technology" will exhibit the characteristics of immediacy, transiency, self-actuation, selectivity, and directness [112]. Intelligent functions and characteristics of materials are the basis for the creation of smart and intelligent systems and environments (Fig. 35.11). Nowadays, numerous artificial smart materials are known, some examples of which are shown in Table 35.1 [112].

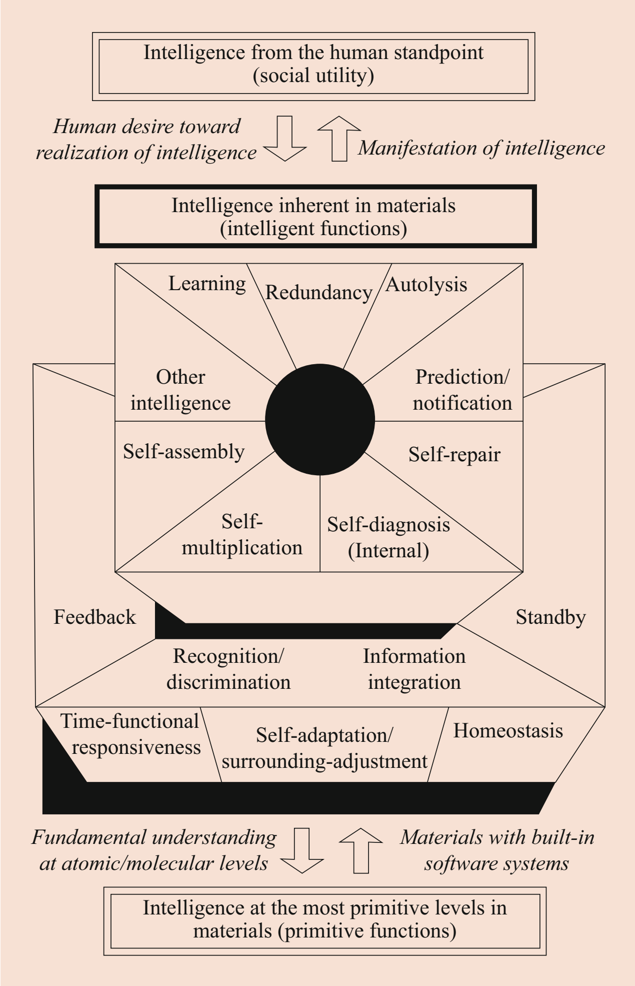


Fig. 35.9 Intelligence inherent in materials [100]

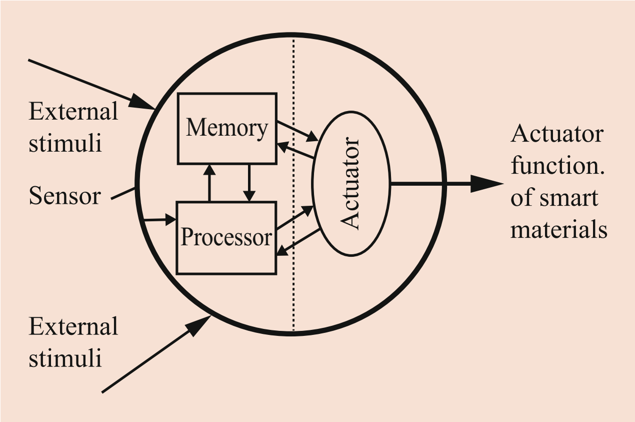


Fig. 35.10 Concept of an intelligent material. (Reprinted from [109], with permission from Elsevier)

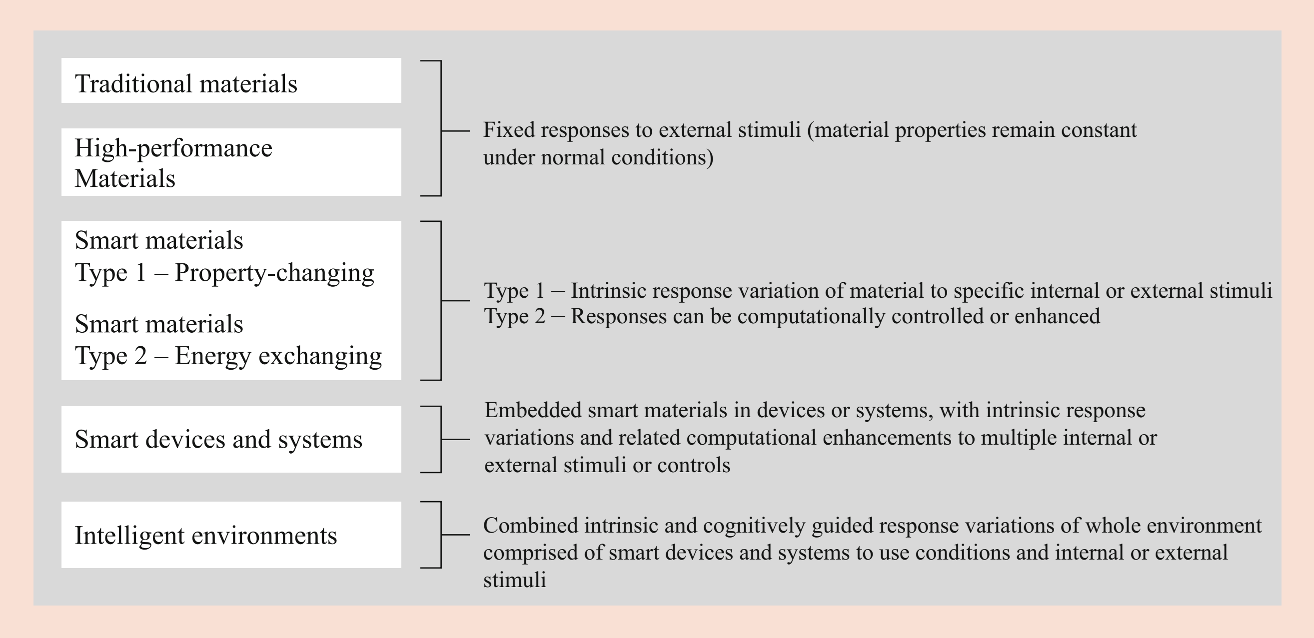
Wood-Based Smart Materials

It is paradoxical that all artificial materials eventually yield to relatively weak and malleable biological prototypes, which turn out to be more rational and reliable. Nature, during the eras evolution, has found and successfully uses for even the simplest species a remarkable ability to flexibly adapt its structure in response to external influences [111, 117, 122, 128]. The composite structure of wood, the hierarchy of levels of structural organization; agile interphase boundaries; variability of characteristics in volume; the presence of soft, flexible components in the structure; self-assembly, self-organization, and self-multiplication give to wood as a traditional construction material the renewable resource to demonstrate the properties of a smart material [129–131]. Features and characteristics of wood as a natural smart material allow to use it to create new smart biocomposite materials, intelligent systems and environments.

The plant cell wall is essentially a hydrogel containing hemicelluloses and pectin reinforced by stiff fibers that hinder deformation in the fiber direction. Anisotropy is induced on at least two length scales due to the orientation of the tubular wood cells and the orientation of the cellulose fibrils within the cell wall. Both these factors limit the freedom of dimensional changes in certain directions, so that hygroscopic swelling may lead to anisotropic deformation and sophisticated movement. The rays may also be in this phenomenon. The pine cone scales are often cited as an example, since they exhibit a sophisticated fiber alignment that facilitates opening of the pine cone during drying. The cellulose fibrils on the outer side of the scales contain cells with a very large microfibril angle, whereas the cells on the inner side has a much smaller microfibril angle [132]. This arrangement leads to a greater longitudinal shrinkage of the outer cells upon drying and therefore a bending and opening of the scales [125].

Describing wood as a natural material, [129–131], Ugolev showed some of the intelligent properties and characteristics of wood. The memory effect of wood that he discovered is a feature of smart materials and allows wood to be included in the class of smart materials [129–131, 133–136].

Shape-memory effect also is evident in the components of the cell wall of wood [137–140]. Li et al. [138] developed lignin-copolymers with elastomeric properties using a long alkyl chain (C12) hyperbranched polyester-amine-amide in a one-pot two-step bulk polycondensation reaction. Copolymer elastomers with a 30% lignin content showed optimal mechanical properties and good Shape-memory effect behavior. The T_{trans} of the lignin copolymers could be tuned by adjusting the lignin content to give a temperature between room temperature and body temperature. Lignin-based triple shape memory polymers consisting of both permanent covalent cross-links and physical cross-links have been synthesized [140]. All the lignin copolymers were elastomeric with great thermally stimulated Shape-memory effect. These polymer systems can be used in medical applications [141] and consumer products where body temperature actuation of the material is required, and this study clearly demonstrates that lignin, a renewable resource and industrial by-product, can be



Traditional materials

High-performance Materials

Fixed responses to external stimuli (material properties remain constant under normal conditions)

Smart materials Type 1 – Property-changing

Smart materials Type 2 – Energy exchanging

Type 1 – Intrinsic response variation of material to specific internal or external stimuli
Type 2 – Responses can be computationally controlled or enhanced

Smart devices and systems

Embedded smart materials in devices or systems, with intrinsic response variations and related computational enhancements to multiple internal or external stimuli or controls

Intelligent environments

Combined intrinsic and cognitively guided response variations of whole environment comprised of smart devices and systems to use conditions and internal or external stimuli

Fig. 35.11 Distinguishing smart and intelligent systems and environments [112]

Table 35.1 Examples of different Type 1 and Type 2 smart materials in relation to input and output stimuli [113]

Type of smart material	Input	Output
Type 1 Property-changing		
Thermomochromics	Temperature difference	Color change
Photochromics	Radiation (Light)	Color change
Mechanochromics	Deformation	Color change
Chemochromics	Chemical concentration	Color change
Electrochromics	Electric potential difference	Color change
Liquid crystals	Electric potential difference	Color change
Suspended particle	Electric potential difference	Color change
Electrorheological	Electric potential difference	Stiffness/viscosity change
Magnetorheological	Electric potential difference	Stiffness/viscosity change
Type 2 Energy-exchanging		
Electroluminescents	Electric potential difference	Light
Photoluminescents	Radiation	Light
Chemoluminescents	Chemical concentration	Light
Thermoluminescents	Temperature difference	Light
Light-emitting diodes	Electric potential difference	Light
Photovoltaics	Radiation (light)	Electric potential difference
Type 2 Energy-exchanging (reversible)		
Piezoelectric	Deformation	↔ Electric potential difference
Pyroelectric	Temperature difference	↔ Electric potential difference
Thermoelectric	Temperature difference	↔ Electric potential difference
Electrorestrictive	Electric potential difference	↔ Deformation
Magnetorestrictive	Magnetic field	↔ Deformation

promisingly increased in value for use as a net-point segment in biobased polymer systems with Shape-memory effect behavior.

The pine cone is essentially a bimorph, i.e., a laminate of two layers, one of which can swell and shrink with changing humidity, while the second acts as a passive kinematic constraint. Using this principle, a variety of biomimetic humidity-driven actuators have been developed. An excellent review is given by Li and Wang [144]. One possibility is to laminate two wood layers with different properties, for example, different microfibril angles, different tree species, or different orientations of wood cells. Such actuators can be designed as large parts and can be used, e.g., for the movement of solar panels [143] or for responsive skins of buildings up to full-scale façades [144, 145], as shown in Fig. 35.12. A comprehensive review is found in [146].

The same concept can be used in artificial bioinspired actuators, and this has become a novel and exciting field of research. Nano-layered bimorphs have, for example, been fabricated from alternately stacked thin films of carbon nanotubes and polyurethane as the passive support with a swellable polyelectrolyte multilayer on top. By printing selective patterns of polyelectrolyte onto the support structure, hinges could be generated which made it possible for the layer to fold as a result of a humidity change [147]. Extending

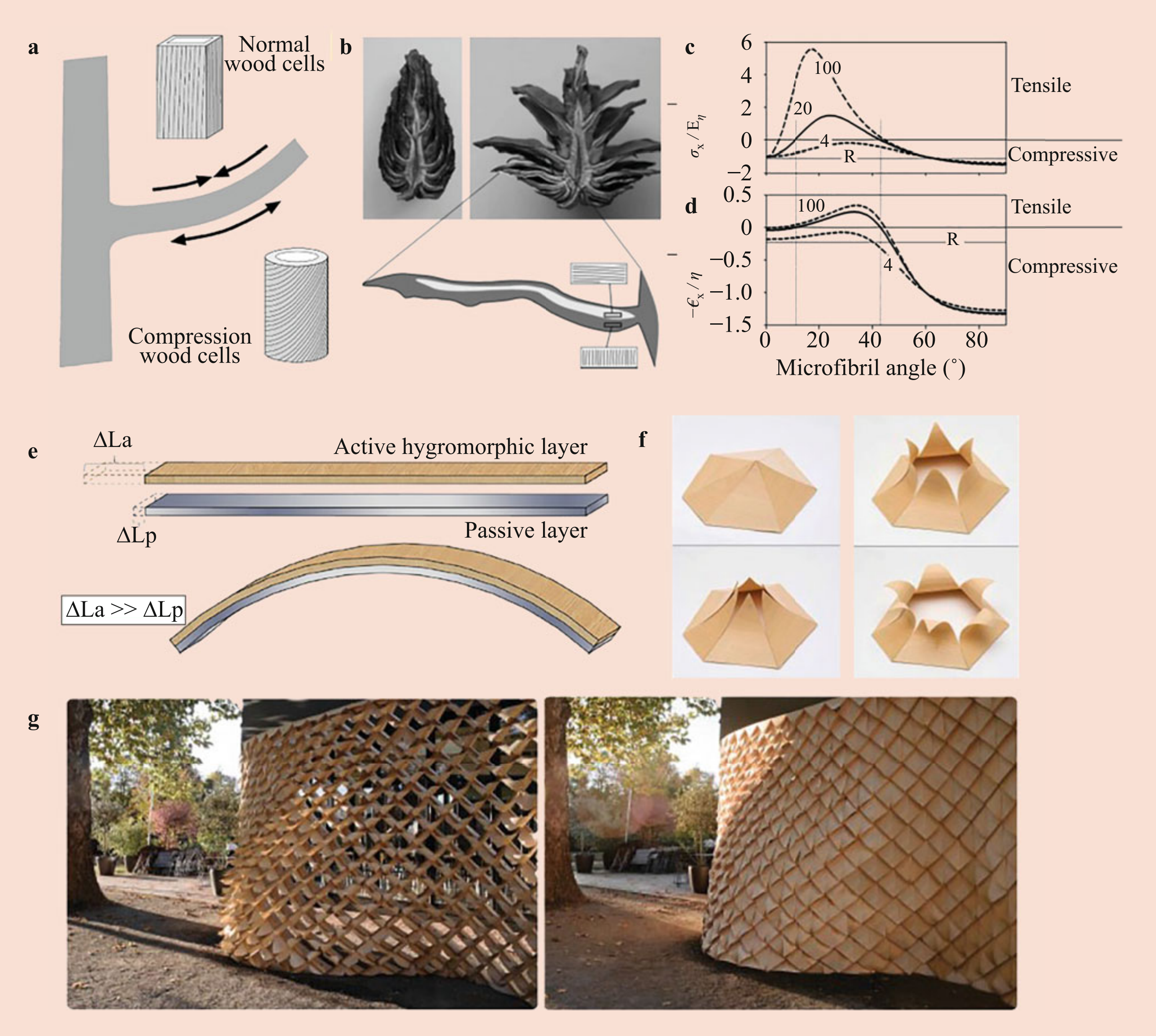


Fig. 35.12 (**a**) Typical orientation of cellulose microfibrils in conifers (normal wood with steep orientation of cellulose microfibrils, compression wood from the underside of a branch with a slow spiral, providing a "push-up" effect upon lignification), (**b**) pine cone opening: different cellulose fibrils on the top and beneath the cone scale cause anisotropic shrinkage upon drying (Diagram taken from [132] and reprinted with permission from [125]), (**c**) and (**d**) axial stresses and strains in a tube-like structure consisting of a swelling matrix reinforced with fibrils strongly depend on the microfibril angle (Reprinted with permission from [125]), (**e**) a bimorph with active (swellable) and passive layers (Reproduced with permission from [146]), (**f**) example of a wooden structure based on a wooden bimorph, and (**g**) wooden bimorphs as a façade structure. (Reprinted with permission from [142])

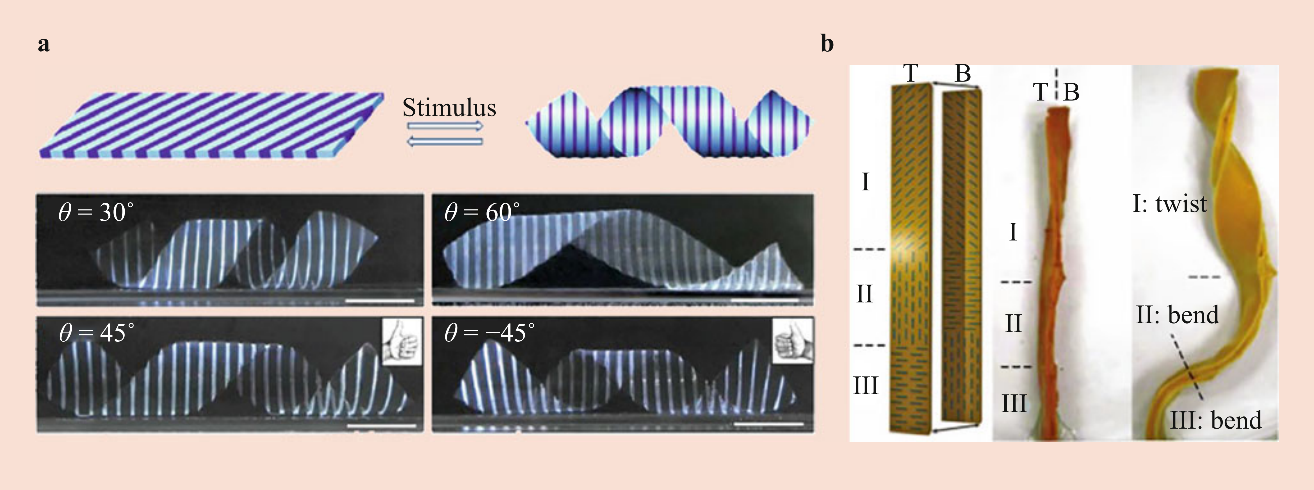


Fig. 35.13 (**a**) Artificial actuator consisting of a composite gel patterned with 1 mm-wide stripes of PNIPAm gel (light blue) and PNIPAm/PAMPS gel (dark blue), the first of which shows a much higher swelling in NaCl solutions above a certain salt concentration. Top: diagram, bottom: actual object with different angles of inclination of the stripes and different curling behavior (Reproduced with permission from [86]). (**b**) Short fiber composites with various orientations of the fibers. Left: a possible bilayer structure, middle: object realized as an alumina-gelatine bilayer composite, right: Swelling leads to programmed curling and twisting. (Reproduced with permission from [150])

this strategy to more than two materials with different combinations and patterns, more complex movements can be achieved. Bending and twisting can be achieved using single layer sheets with three different materials [148, 149] (Fig. 35.13).

The closest similarity to a plant tissue is given by a fibrous system, where rigid fibers are usually implemented in a humidity-responsive hydrogel. Armon et al. have fabricated an analogue to opening chiral seed pods using fiber-reinforced latex strips [151]. Responsive fibers in a passive matrix are also conceivable. Flax fibers in a passive polypropylene matrix have, for example, been used to achieve bending [152]. Depending on the fiber orientation, more complex patterns of motion can be achieved. The orientation of long fibers is rather challenging, in particular if the fibers are of micrometer or nanometer size, but the dispersion and orientation of short fibers or platelets is easier to handle. This approach has been used by Erb et al. to fabricate a hygroscopic composite with three different fiber orientations [150]. Alumina platelets coated with iron oxide nanoparticles were dispersed in a hydrogel and oriented in a magnetic field, different platelet orientations being achieved by either rotating the magnet or rotating the sample in the magnetic field. As a matrix, the authors used hygro-responsive gelatine and thermo-responsive PNIPAAm (Poly(N-isopropylacrylamide)) as actuators. Bilayers and monoliths containing different and sometimes alternating platelet directions have been produced with controlled bending and twisting movements [153].

The complicated hierarchical structure, the features of interaction of components of wood substance, and the behavior of wood when various factors are changed are described in detail in ▶ Chaps. 3, ▶ 5, ▶ 6, and ▶ 7, in this Handbook.

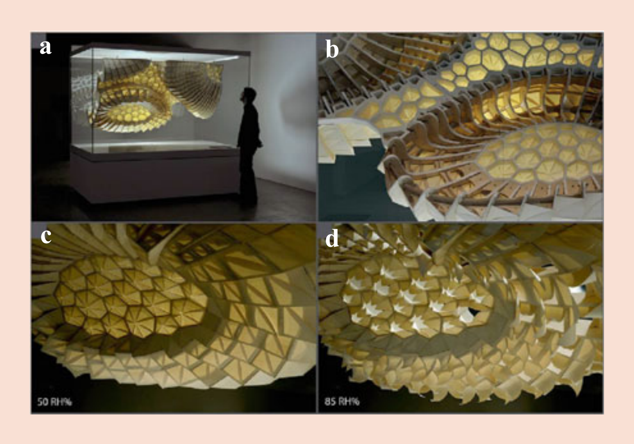


Fig. 35.14 HygroScope installation at the Centre Pompidou, Paris, France [145]: (**a-d**) different modes of opening due to relative humidity in the surroundings

Reichert et al. at the Institute for Computational Design (ICD) in Germany developed Biomimetic Responsive Surface Structures [154–156], where the anisotropy and hygroscopy of wood are utilized so that the dimensional changes triggered by changing climatic conditions are exploited to induce shape changes in reactive material elements. In a project entitled "HygroScope: Meteorosensitive Morphology" (Centre Pompidou, Paris, 2012) [145], they explored the transfer of biological principles to architectural systems based on hygro-copically actuated wood-veneer composite systems. Suspended within a humidity-controlled glass case, the model opens and closes in response to climate changes with no need for any technical equipment or energy (Fig. 35.14a,b). Fluctuations in relative humidity are sufficient to trigger the silent innate-material movements. The material structure itself is the machine which behaves as an actively moving material [157]. Unlike conventional engineering systems which rely on discreet functional components (sensors, actuators, and controllers), biological systems rely on differentiated materials and structured material systems that are at the same time sensor, actuator, and regulator.

Later et al. suggested the first building application of meteoro-sensitive morphology [158–160], where the project *HygroSkin – Meteoro-sensitive Pavilion* explores a mode of climate-responsive architecture (Fig. 35.15), and the dimensional instability of wood in relation to moisture is employed to construct a metereo-sensitive architectural skin that automatically opens and closes in response to weather changes requiring neither a supply of operational energy nor any kind of mechanical or electronic control. The traveling pavilion's modular wooden skin is designed and produced utilizing the self-forming capacity of initially flat laminated-veneer sheets to form conical surfaces based on the material's elastic behavior. The material adapts its form in unison with the environment.

Bioinspired 3D-printed hygroscopic-programmable-material systems for architecture were developed by teams at ICD and Massachusetts Institute of Technology (MIT) [161–163]. Computational design and digital fabrication of climate-responsive material systems were used to expand earlier investigations of meteoro-sensitive morphology and use numerically controlled, additive layer-manufacturing technologies at a material level. By utilizing multimaterial 3D-printing technologies and anisotropic material compositions, it was possible to program hygroscopic materials such as wood to sense and self-transform based on fluctuations in the environment (Fig. 35.16). New methods were presented for designing hygroscopic wood transformations and for developing customized techniques for energy activation. A multimaterial-printing method provides greater control and makes possible intensified wood transformations through the precise design printing of both synthetic wood and polymers (Fig. 35.17). Flat sheets of printed wood composite can be designed to self-transform in controlled and unique ways. Water is used as a medium for activation, and it is planned to develop wooden composites that can adapt to extreme environmental conditions. The methods, techniques, and material tests presented have demonstrated the first successful results of differentiated printed wood for self-transforming behavior, suggesting a new approach for programmable materials and responsive architectures.

Rüggeberg and Burgert developed bioinspired wooden actuators for large-scale applications using the bilayer principle [164]. They demonstrated the actuation of wooden bilayers made of European beech and Norway spruce strips in response to changes in relative humidity, making use of the high-material stiffness and a good machinability to reach large-scale actuation. Field tests in full weathering conditions revealed the long-term stability of the actuation. With the sensor and actuator intrinsically incorporated in the wooden bilayers, the daily change in relative humidity was exploited for the automatic solar-powered movement of a tracker for solar modules.

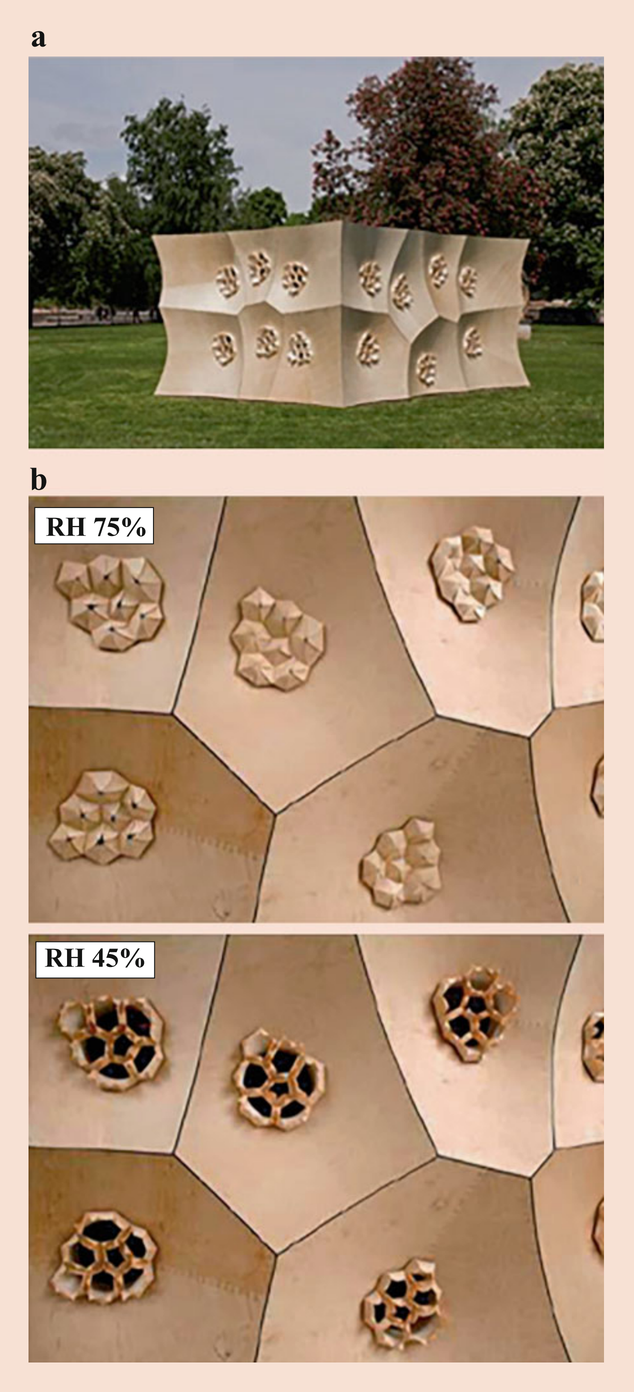


Fig. 35.15 The HygroSkin Pavilion project at FRAC Centre, New Orleans, USA, 2013: (**a**) HygroSkin Pavilion, and (**b**) the hygroscopic apertures in different states (relative humidity (RH) 75% or 45%) [159]

Hygroscopically actuated wood elements have been suggested for weather-responsive and self-forming building components [165]. Design principles for achieving a range of shape-changing patterns such as uni- and bidirectional surface curvature of wood and wood-hybrid bilayers with both negative hyperboloid curvature and positive spherical curvature have been demonstrated. With a large glass-fiber-reinforced polymer and wood composite bilayer comprising an assemblage of wood elements (Fig. 35.18), Rüggeberg and Burgert demonstrated synclastic curvature by the anisotropic swelling of wood and the restrictions in swelling introduced by the orientation of the wood elements. The

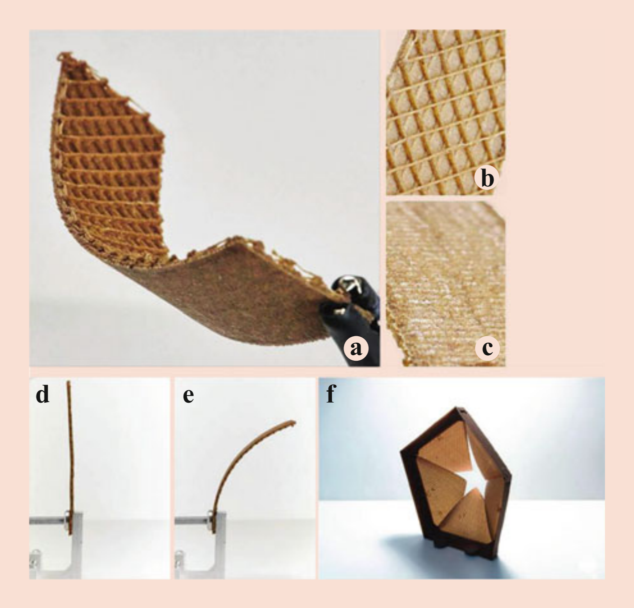


Fig. 35.16 (**a**) Single-material 3D-printed test sample developed by the Institute for Computational Design (ICD) showing (**b**) grid pattern and layer details, and (**c**) curling wood-grain-layer detail. Curling states under (**d**) high RH and (**e**) low RH, and (**f**) a single-material 3D-printed aperture previously developed by ICD that shows the functional grading from the static frame like perimeter support to the weather-responsive central region [162]

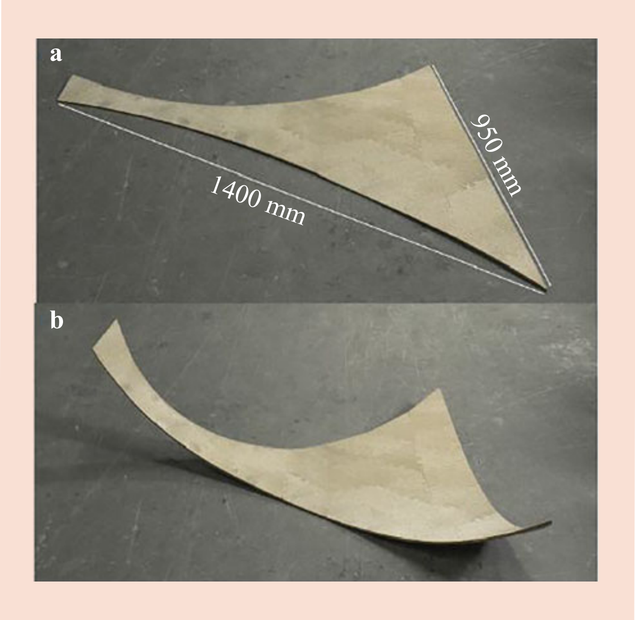


Fig. 35.18 Synclastic curvature of a multielement wood-GFRP bilayer: (**a**) flat state, and (**b**) curved state [165]

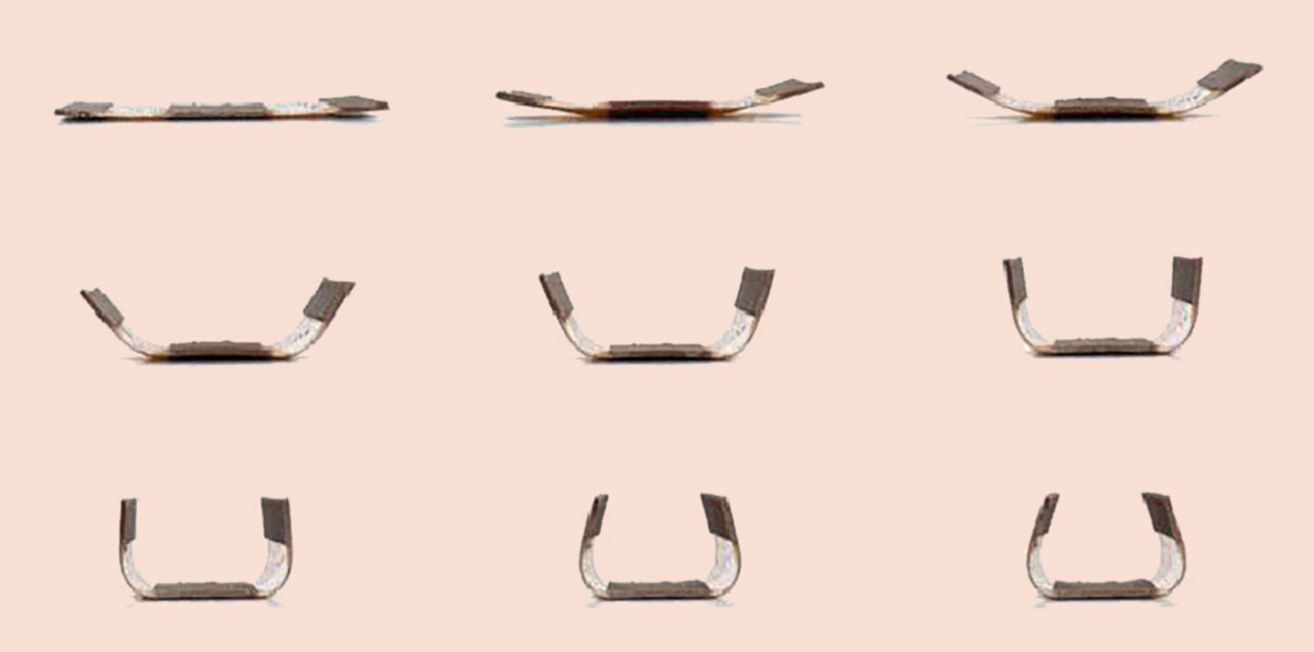


Fig. 35.17 A series of photographs showing a multimaterial printed wood composite developed by the Self-Assembly Lab at Massachusetts Institute of Technology (MIT), that self-transforms from a flat sheet into a symmetrically folded structure [162]

ability to design and control the type and magnitude of curvature for chosen sizes, shapes, and aspect ratios opens the way to a new class of large-scale weather-responsive elements and self-forming building components.

A plant-based torsional actuator with memory was developed by Plaza, Zelinka, Stone, and Jakes [166, 167]. A bundle of loblolly pine cells are moisture-activated torsional actuators that twist multiple revolutions per cm of their length in direct proportion to the moisture content. The torque generated by the moisture-induced twisting and untwisting of a wood cell bundle is shown in Fig. 35.19. When the humidity is increased from 3% to 94% RH, this bundle produced a torque of 25 Nm/kg, which is higher than that produced by an electric motor and possesses shape memory twist capabilities. The authors also reported that the diffusion of ions through wood cell walls is a stimuli-responsive phenomenon. The bundles demonstrate a high-specific torque actuator with large angles of rotation and shape memory twist capabilities that can be utilized in microactuators, sensors, and energy harvesters.

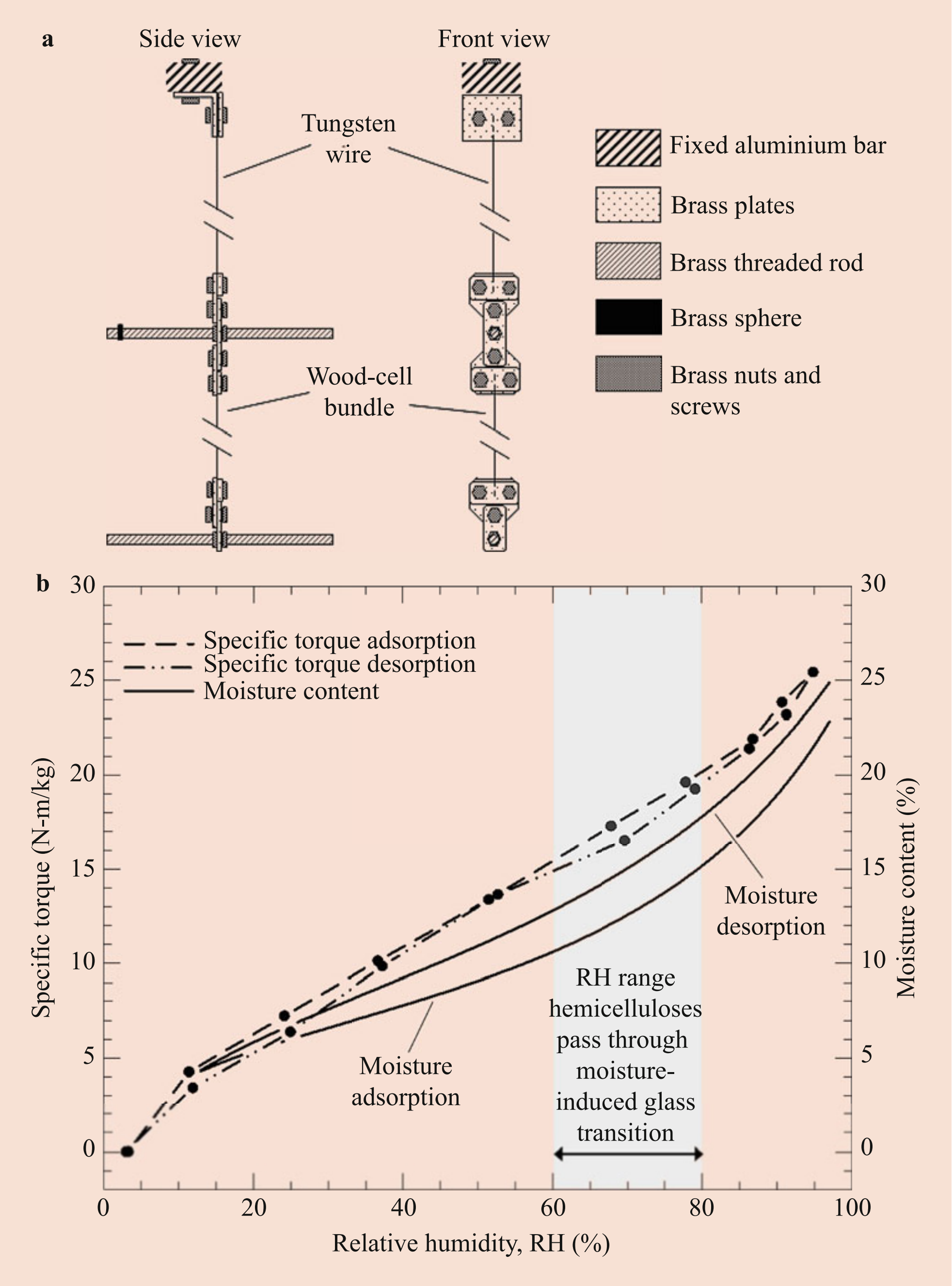


Fig. 35.19 Plant-based torsional actuator with memory: (**a**) connector design for tungsten wires and cell bundles, and (**b**) specific torque as a function of relative humidity (RH) generated during conditioning as assessed by the custom-built torque sensor [167]

Gorbacheva et al. [168] proposed a compact mobile sensor to measure relative humidity which does not use any external energy source. A sample of birch veneer is used as a sensitive element fixed on a substrate equipped with a scale with marked zones of "comfortable" relative humidity.

The combination of mechanical properties [169] and stimuli-responsive behavior is very interesting and should inspire the development of new stimuli-responsive structures and materials based on wood. Wood has been employed as a smart material for an automatic shading system based on coupled wood bilayer elements developed by Vailati et al. [170]. Climate-adaptive building shells can help to reach the desired global reduction of energy consumption in the building sector. Automatic humidity-driven wood bilayers are proposed as an alternative to motor-driven facade-shading elements. Due to the hygro-responsiveness of the wood material, the changes in relative humidity from day to night as well as the drying effect of direct solar radiation can be utilized to induce changes in the wood bilayers to open and close facade-shading systems (Fig. 35.20). They presented the coupling of two wood bilayers as a possible solution to the operation of shading elements.

Holstov et al. [171] considered the sustainable materialization of responsive architecture and they investigated in detail the sustainability of wood-based hygromorphic smart materials (i.e., materials that change shape with changing humidity) for large-scale external applications through a detailed program of experimentation and a one-year-long durability study of hygromorphic wood composites in full weathering conditions, the results of which provide the basis for the design of an optimized responsive cladding system.

Wood has unique properties of smart composites. Wood-plastic composites (WPCs) consisting of wood or other cellulose-based fibers and virgin or waste plastics [172, 173] are often called "smart wood." One of the goals

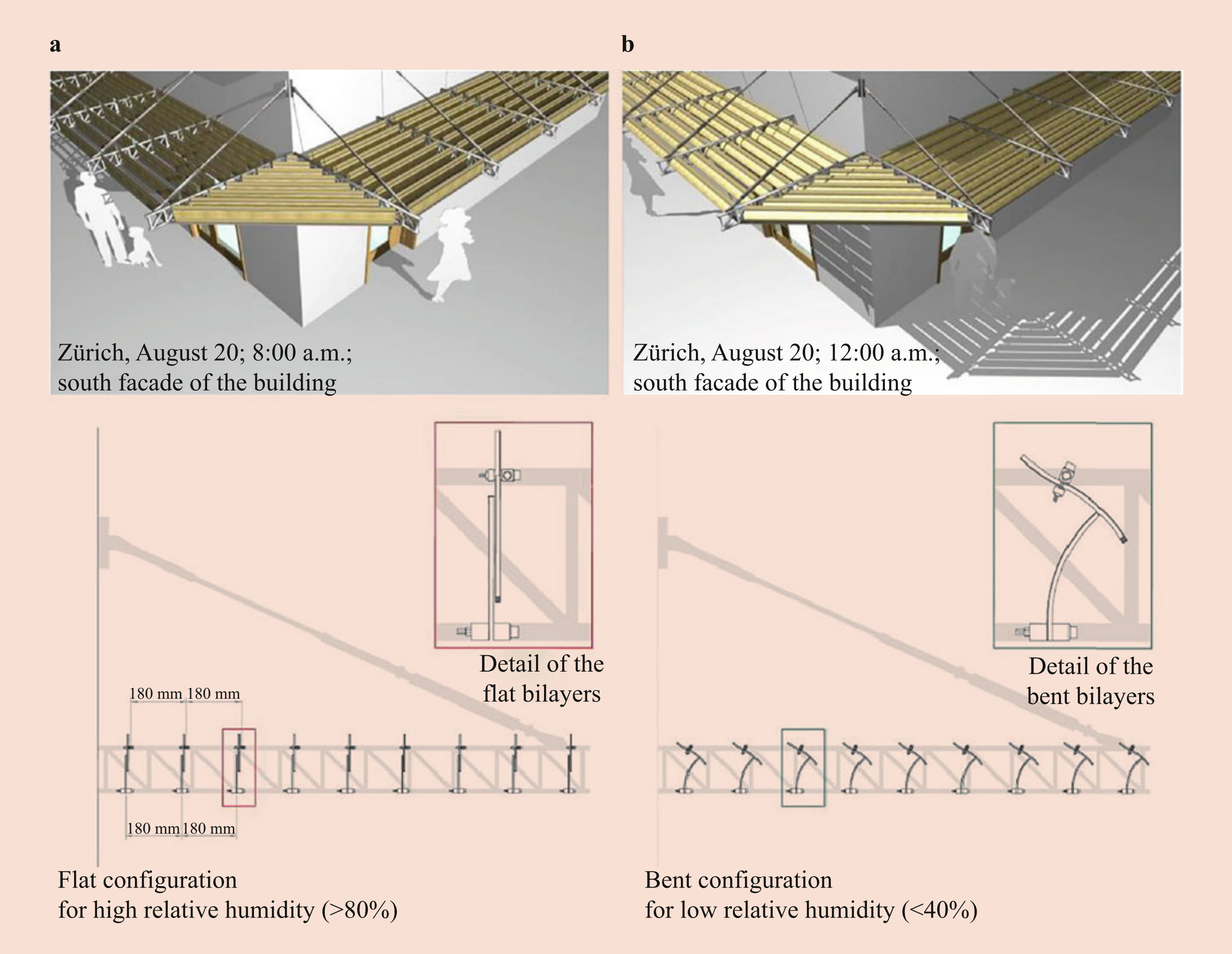


Fig. 35.20 Digital renders and drawings of the cross section of horizontal shading system based on coupled bilayers fixed onto a building façade: (**a**) flat state at high relative humidity, and (**b**) bent state at low relative humidity, insets show the setup of one coupled element [170]

of the “Smart WPC – Development of Functionalized Composites Based on Cellulose for Smart Products” project [174] is to increase the demand for WPCs by incorporating special functionalities (F-WPC) such as electrical conductivity, thermal conductivity, or better mechanical performance. This will enhance the performance of WPCs in applications where they are conventionally used and will open new service sectors.

Nanocellulose opens up limitless possibilities for creating smart materials and devices [175], increasing the multifunctionality of wood materials. Transparent and conductive paper from nanocellulose fibers has been developed by Hu et al. [176] (Fig. 35.21). Using a chemical or enzymatic pretreatment followed by high-pressure homogenization, the micrometer-sized cellulose fibers can be disintegrated into nanofibrillated cellulose (NFC) with a diameter of 10–20 nm and a length of 2 mm. By compressing the NFC pulp in a sheet-former, highly transparent nanocellulose paper can be produced, with a large light-scattering ability in the forward direction, which is useful in solar cell applications. The nanocellulose paper can be coated with a wide variety of conductive materials, such as carbon nanotubes (CNT), silver nanowires (AgNWs), and tin-doped indium oxide (ITO), to produce a transparent conductive paper. By depositing a thin layer of ITO, the conductive nanocellulose paper can be used as a substrate for organic solar cells.

Yao et al. [177] developed a smart triboelectric nanogenerator (TENG) and power-boards from cellulose nanofibrils (CNFs) and recycled materials (Fig. 35.22). Flexible and transparent CNF films are a triboelectric positive material with nanoscale surface roughness. They are paired with FEP (fluorinated ethylene propylene) to create TENG devices, with a performance comparable to that of the TENG devices built on synthetic polymers. CNF-based TENG is further integrated within a fiberboard made from recycled fibers using a chemical-free cold-pressing method. The fiberboard produces an electric output of up to ~30 V and ~90 μA when subjected to a normal human step. Calculations show that the power fiberboard has a charge transfer efficiency of up to 98%. This development showed a great promise for creating large-scale and environmentally sustainable triboelectric wood panels, fiberboards, or floorings. Combining the unique energy-harvesting capability and eco-friendliness of CNFs and wooden fibers, it is foreseeable that CNFs and other natural wood-extracted materials will play an important role in the development and manufacture of industrial-level flooring, packaging, and supporting infrastructures capable of effectively harvesting mechanical energy from the ambient environment.

Wood veneer was used to produce a plywood composite with good shielding effectiveness (SE) by Yuan et al. [178]. Carbon fiber paper (CFP), thin flexible planar electromagnetic shielding material with low density, and good adhesion and permeability, was laminated with wood veneer to produce a material that could also be used as a shielding material. In the frequency range of 30 MHz to 1 GHz, reached above 30 dB depending on the space between two-layer CFPs and

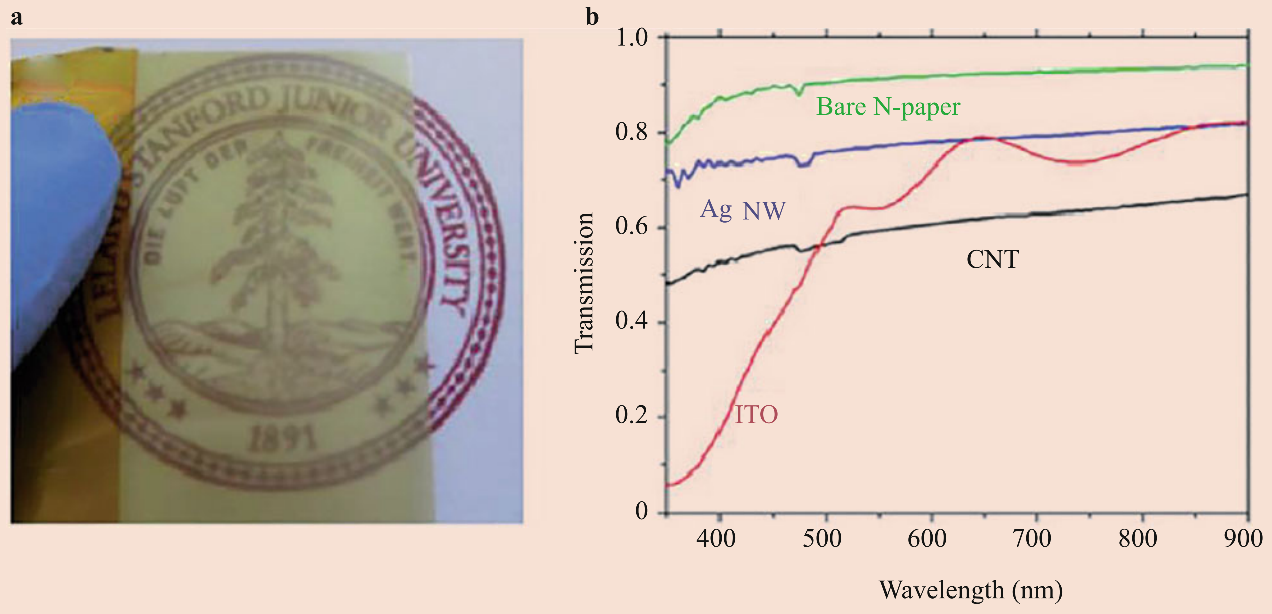


Fig. 35.21 Transparent conductive nano-paper: (**a**) Conductive nano-paper based on ITO with a performance of 12 Ω sq-1 and 65% total transmittance at 550 nm, and (**b**) diffusive transmittance versus wavelength for conductive nano-papers coated with CNT, ITO, and AgNWs [176]

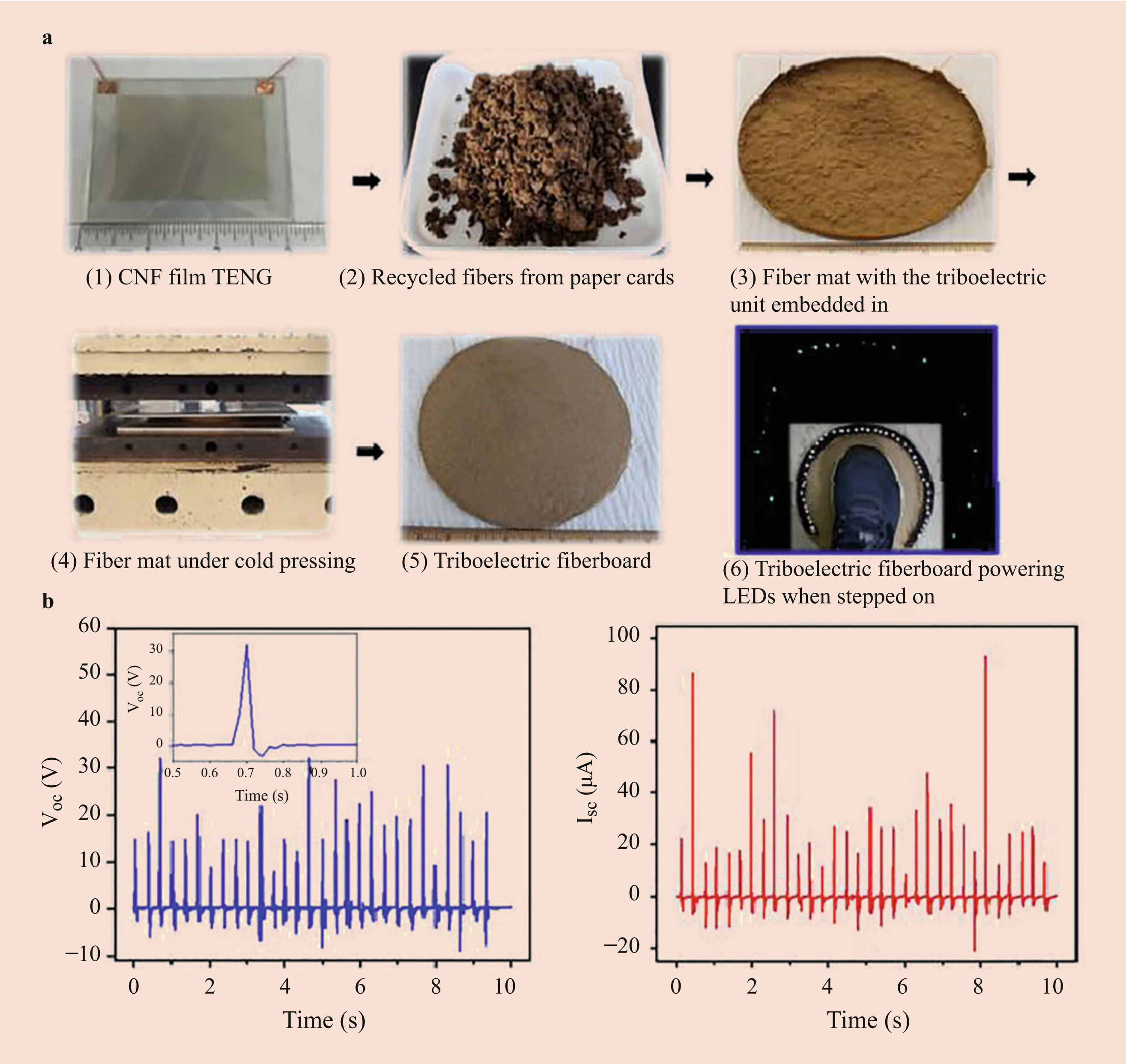


Fig. 35.22 Manufacture and performance of CNF-based TENG fiberboard: (**a**) manufacture of triboelectric fiberboard, (**b**) open-circuit voltage (V_{oc}), and (**c**) short-circuit current (I_{sc}) output of the triboelectric fiberboard when a person of normal weight stepped on it repeatedly. Inset in (**b**) is the V_{oc} during one step [177]

the thickness of the surface veneer, which was sufficient SE for commercialization, and plywood composites are being used to reduce harmful electromagnetic interference in the fields of military, precision instruments, and hospital equipment.

Bertolini et al. [179] used smart materials in timber constructions belonging to our cultural heritage. Nano-structured materials to protect and reinforce timber structures have been described by Marzi [180].

Lv et al. [181, 182] developed wood-based solid-state supercapacitors (Fig. 35.23) using polypyrrole (PPy) or reduced graphene oxide (RGO) coated onto a wooden transverse section slice (WTSS) as electrode material by a low-cost, eco-friendly, and simple method. The RGO-coated and PPy-coated WTSS electrodes have a porous 3D honeycomb framework due to the hierarchical cellular structure of the WTSS substrate and can function as an electrolyte reservoir. The RGO-coated WTSS special construction gives this electrode a good areal capacitance (102 mF cm^{-2}) and excellent cyclic stability (capacitance retention of 98.9% after 5000 cycles). In addition, the supercapacitors exhibit good mechanical flexibility and

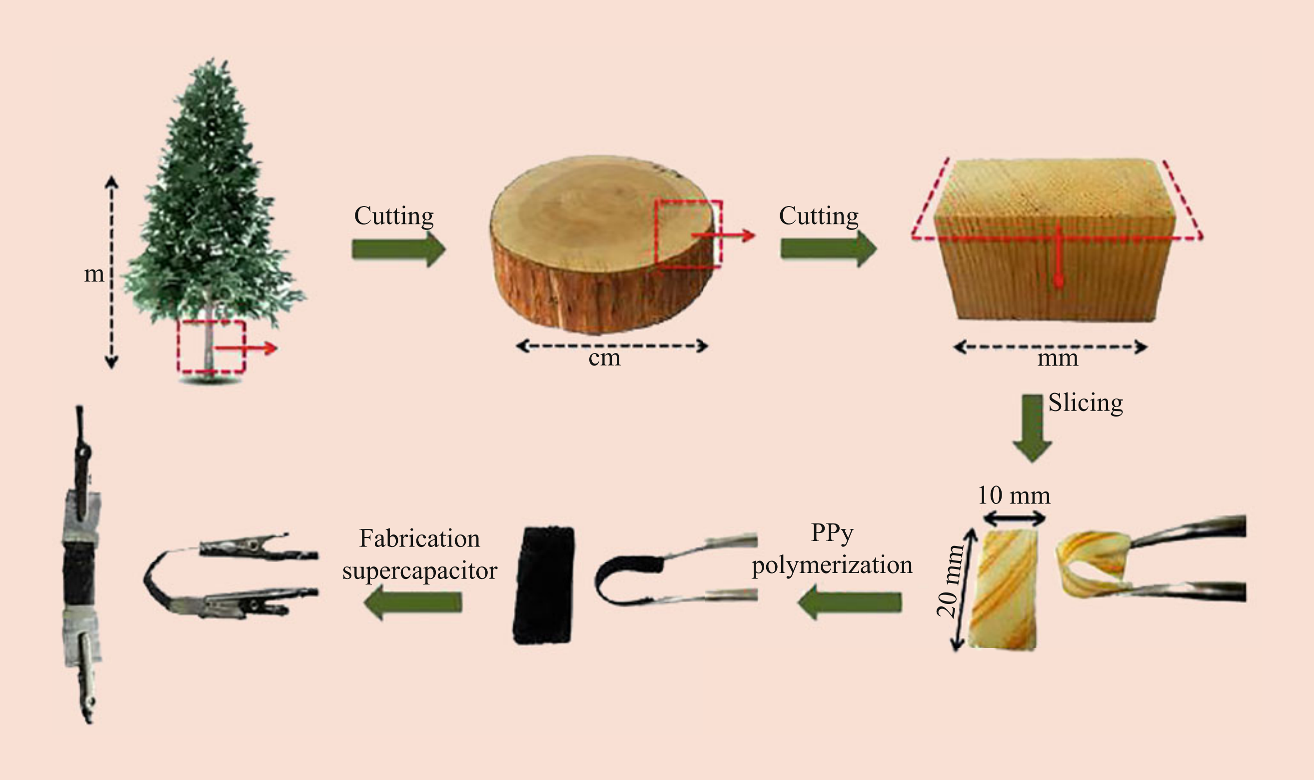


Fig. 35.23 The preparation of native WTSS, WTSS/PPy, and its supercapacitor [181]

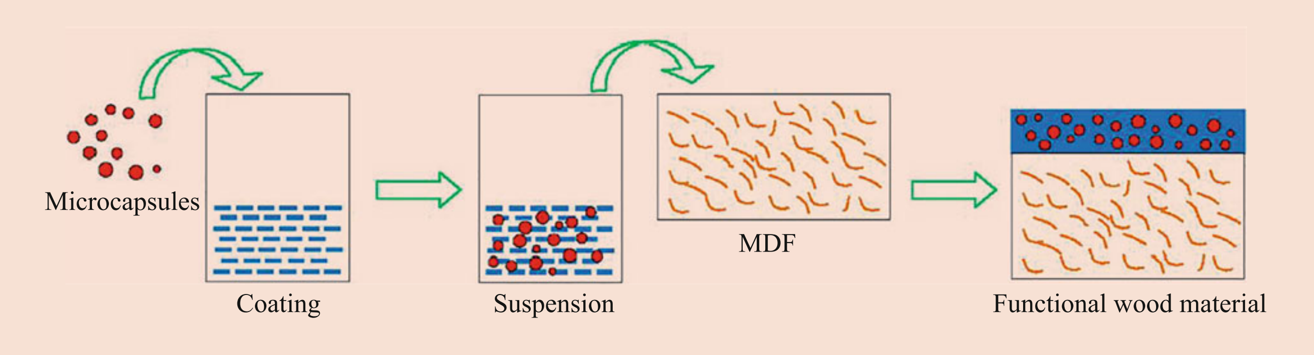


Fig. 35.24 The preparation of a wood functional material [184]

preserve almost constant capacitive behavior under different bending conditions. This study introduced a new and eco-friendly material design for electrodes in future flexible energy storage devices that closely resemble natural materials.

Liu et al. [183] created a smart thermochromic wood. Poplar veneer is impregnated with a thermochromic agent consisting of a thermochromic dye, a chromogenic agent, 1-tetradecanol, and a sensitizing agent at a ratio of 1:8:50:1. The color of these products changed from blue to wood color as the temperature was increased from 26 to 34 °C and reverted blue when the temperature was decreased to 26 °C.

Hu et al. [184] developed a smart multifunctional wood material by incorporating thermochromic energy-storage microcapsules into coatings on medium density fiberboard (MDF) (Fig. 35.24). The microcapsules demonstrated a sensitive color-change phenomenon with a latent heat of over 90 J/g. The surface color of the coated MDF changed between blue and light brown within a temperature range of 20–39 °C, with a “colour hysteresis” phenomenon. The coated MDF could be considered to be an energy-storage material with a phase-change temperature range of 12–38 °C. The multifunctional MDF could be used as a decorative and thermoregulating material.

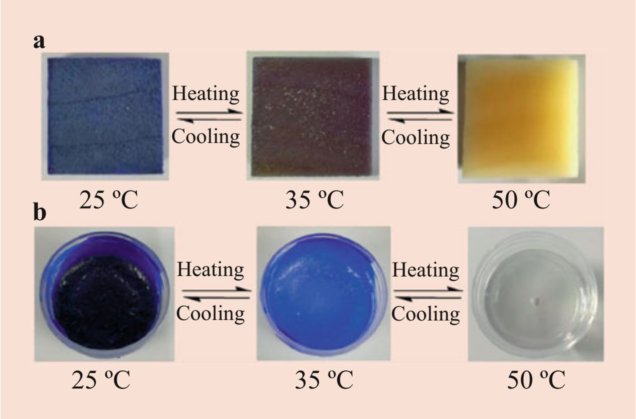


Fig. 35.25 Photographs of (**a**) TCDWs and (**b**) TC compound at 25, 35, and 50 °C [185]. The thermochromic changes are reversible

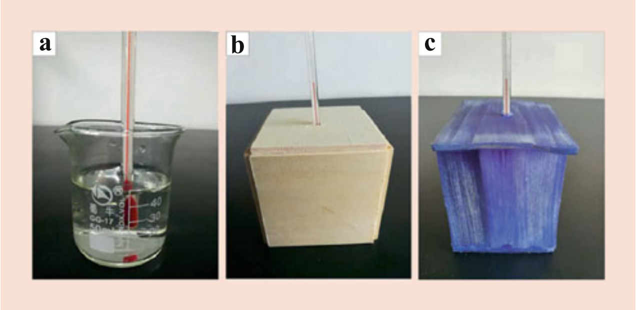


Fig. 35.26 Photographs of temperature-time test process: (**a**) DI water (50 mL) at 80 °C in beaker kept static, (**b**) DI water (50 mL) at 80 °C in beaker placed in a PW box, and (**c**) DI water (50 mL) at 80 °C in beaker placed in a TCDWs box and allowed to cool to room temperature [185]

Composite materials with a good reversible thermochromic function in a delignified wood substrate for thermal energy storage were developed by Yang et al. [185]. The thermochromic delignified wood (TCDW) composite material consists of a thermochromic (TC) compound and delignified wood (DW) and is fabricated by vacuum-assisted impregnation. These TCDWs have an excellent reversible thermochromic ability and visibly change from dark blue to off-white (Figs. 35.25 and 35.26). The absorption capacity of DW is 65%, which is 15% more than that of pristine wood (PW). TCDWs have a great potential in thermal energy storage applications, including thermal insulation, decoration, furniture, storage, and building energy conservation.

Li and Li [186] made a smart reversible thermoresponsive wood with a hydrophobic performance by depositing a thermoresponsive coating on the wood surface. The coating was prepared from thermochromic materials (TM) supported on 3-aminopropyltriethoxysilane (AEPT) in a polyvinyl alcohol solution (PVA) (Fig. 35.27). All the samples were reversibly thermoresponsive, the thermochromic response rate of TM-APTES-/PVA-modified wood being higher than that of the other samples. The surfaces of wood materials changed from being hydrophilic to being hydrophobic after chemical modification.

Hu et al. [187] developed a smart, color-changing wood material by incorporating photochromic thermally stable microcapsules into coatings on veneered plywood. The photochromic wood material spontaneously changed from the veneer color to a blue color when exposed to sunlight. The incorporation of microcapsules did not affect the coating adhesion, but it reduced the coating wearability. A simple

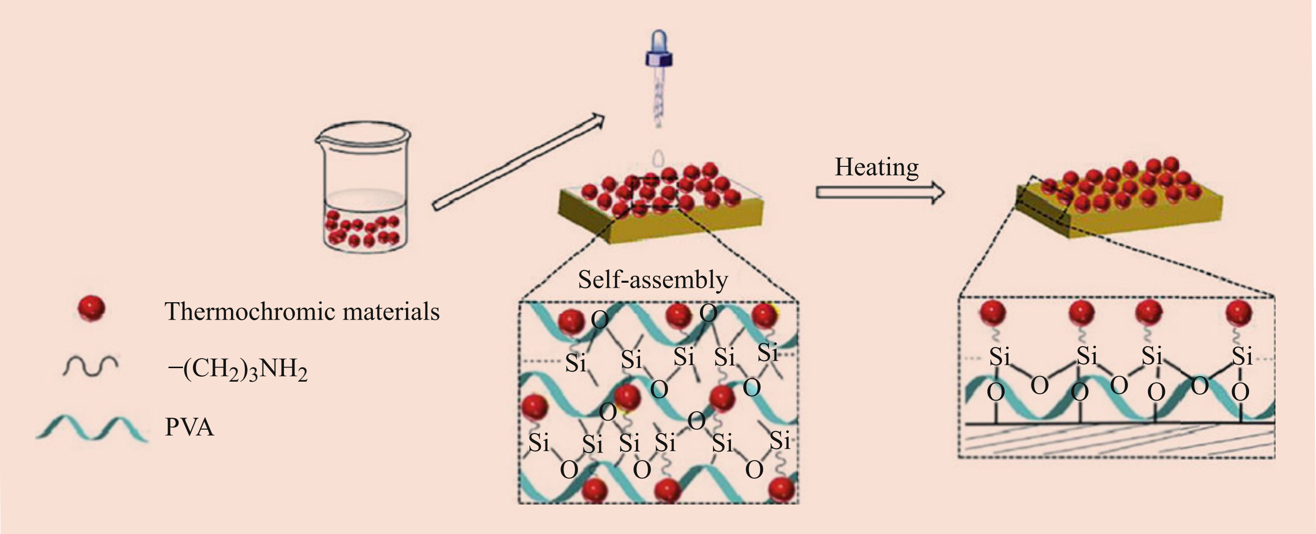


Fig. 35.27 The mechanism for producing TM-APTES-/PVA-coated wood [186]

application of this smart wood material is shown in Fig. 35.28, where blue graphics are displayed on the surface of a sample panel. The reversible properties of photochromic wood products can provide dynamic decorative effects similar to those of thermochromic wood materials [185] showing a potential for furniture, decoration materials, and wood artworks as indicators of ultraviolet or sunlight.

Multifunctional wood materials with magnetic, superhydrophobic, and antiultraviolet properties were developed by Gan et al. [188] using of CoFe2O4 nanoparticles and octadecyltrichlorosilane (OTS), as shown in Figs. 35.29 and 35.30. The saturation magnetization (MS) and coercivity (HC) of the magnetic wood were 1.8 emu/g and 450 Oe, respectively. The contact angle (CA) of water on the treated wood was around 150°, and the modified wood also showed a superior antiultraviolet performance.

In conclusion, it can be said that the properties of wood as a natural smart material, rapid advances in chemistry, and digital fabrication technologies make it possible to create new smart multifunctional materials and expand the traditional uses of wood and wood-based materials. Wood is the advanced material of the future and, as such, is becoming increasingly important. Social awareness of the need for resource conservation and simultaneous technical developments are bringing mankind's oldest material back into the spotlight.

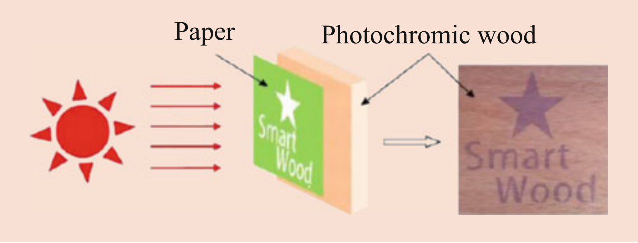


Fig. 35.28 Application of an image on a photochromic wood material [187]

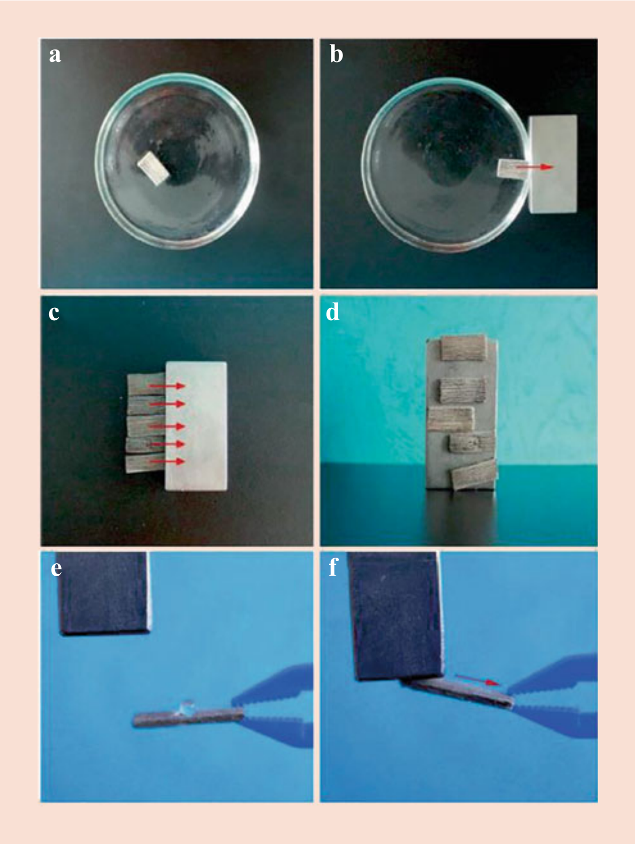


Fig. 35.30 Superhydrophobic and magnetic wood samples, under the influence of an external magnet (**a** and **b**), a floating specimen moves toward the magnet (**c** and **d**), and actuation of a magnetic wood platelet (**e** and **f**). The water droplet drops from the wood surface by driving the magnetic wood [188]

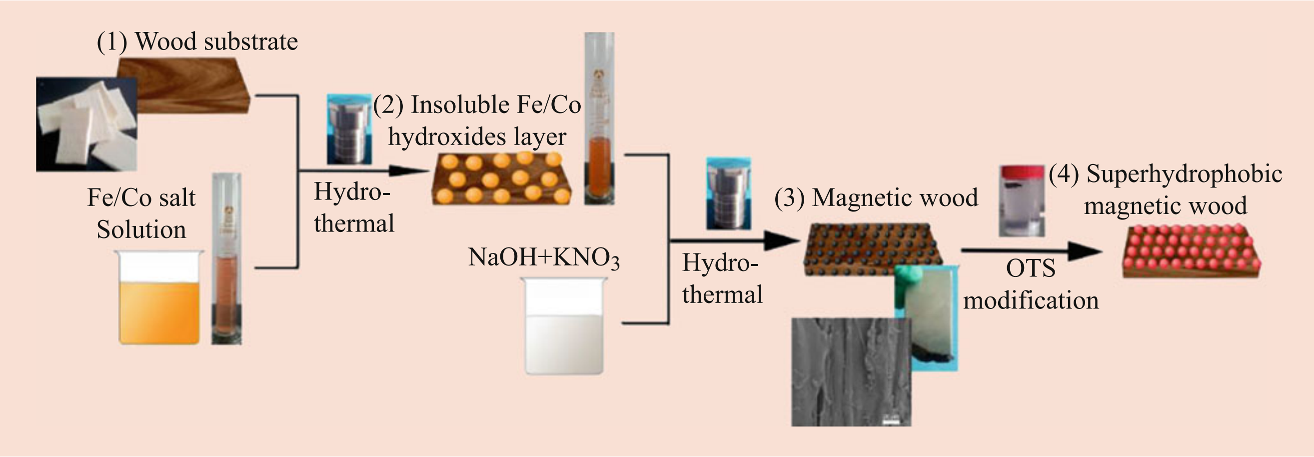


Fig. 35.29 Preparation of superhydrophobic and magnetic wood [188]

35.3 Multifunctional Wood Elements

The term *multifunctional wood elements* applies to engineered wood products (EWPs) that not only have load-bearing capacity but also additional properties such as acoustic, heat transfer and light-weight properties, and an extraordinary shape stability, as well as hybrid functions, a greater ability to form a given shape, installation solutions, and an esthetic and tactile performance. The traditional EWPs of this kind are I-beams/I-joists and box-beams. The overall purpose of using multifunctional wood elements is to make the prefabrication and on-site assembly more effective. Some multifunctional wood elements or EWPs that will be briefly described here are the following:

- Rod-shaped and plate-shaped high-performance load-bearing wood-based elements
- Hybrid wood elements (wood combined with other materials)
- Light-weight elements
- Acoustic elements
- Thermal-insulation elements
- Other special niche products

35.3.1 Rod-Shaped and Plate-Shaped High-Performance Load-Bearing Wood-Based Elements

There is a broad spectrum of rod-shaped engineered load-bearing building components, the currently most important products being I-beams/joist, box-beams, glued-laminated timber (glulam), laminated veneer lumber (LVL), and parallel strand lumber (PSL/Parallam) intended for structural uses (cf. ▶ Chaps. 25 and ▶ 26). The main engineering approaches for such EWPs are the following:

- Homogenization effects (decrease in variability) by strength-graded lamellae or plies (cf. ▶ Chap. 34, aspects of wood utilization and material selection)
- Strength-driven design for the lay-up of the different layers giving superior and predesigned mechanical properties
- Enhancing mechanical properties by using high-density hardwood species with superior properties such as European beech or European ash or combinations of softwood and hardwood laminates or hybrids from solid wood lamination and LVL lamination [189–191]
- There is also the possibility of producing beams with lengths exceeding the limited length of the logs allocated to primary wood processing the joining of glued-laminated timber on the building site beyond the maximum transport length [192, 193]
- Defined geometry in cross-section and in some cases also in the shape of the beams due to architectural and structural design requirements (cf. ▶ Chap. 25)
- Fiber-reinforced glued-laminated timber (cf. ▶ Chap. 25) and reinforced areas of beam support to withstand stresses perpendicular to the grain, shear stresses, etc. [194–197] some examples are shown in Figs. 35.31 and 35.32

In Europe, EWPs for construction are in most cases traditionally made of softwood because of the great availability in continental Europe of large-sized round timber of conifers. Their low density, in combination with a uniform structure and the required mechanical properties, results in a favorable mass-to-strength ratio. Hardwoods have, however, been used increasingly often for the reinforcement of softwood elements [198] and for the use in the entire elements [199]. Glued-laminated timber made of hardwood is a construction element developed in line with the current changes in the forestry industry. During the last decade, there have been intensive studies on hardwoods such as

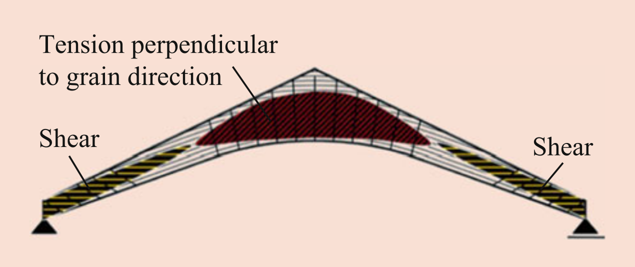


Fig. 35.31 Pitched cambered beam – potential reinforcement zones [197]

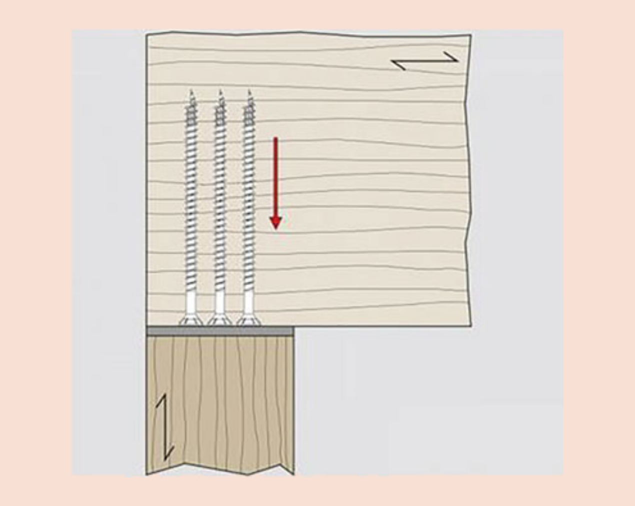


Fig. 35.32 Basic principle of beam support withstanding stresses perpendicular to the grain in vertical supports using self-tapping screws

beech, oak, chestnut, and ash in Europe, and these studies have led to glued-laminated timber with favorable mechanical characteristics and the provisional approval for their use in construction [199].

Dietsch et al. [196–198] provide a state-of-the-art reinforcement approach with a special focus on self-tapping screws. Their economic advantages and comparatively easy handling make them one of the first choices for application requiring both shear and tension perpendicular to grain, and self-tapping screws and threaded rods are applied as reinforcement in many applications. There is not only a basic principle of reinforcement to withstand compression in a vertical beam support as shown in Fig. 35.32, but also reinforcement of the softwood with a hardwood such as oak occurs in practice.

Glued-laminated timber with a free span of about 50 m and a total length of about 100 m can be produced and incorporated in constructions. Glued-laminated timber composed of LVL laminations has extraordinarily strong mechanical properties and is placed in strength classes up to GL 70 (cf. Sect. 25.3), when made of beech wood [200]. Such high-strength building elements can be used in slender structures, for heavy loads and large spans, but various constraints in the manufacturing process and especially on the building site, e.g., difficult and harsh workability of the hardwood components with hand tools, have to be considered.

Specific engineering approaches address specific situations in order to enhance the performance of glued-laminated timber. Dietsch [196] discusses the introduction of reinforcements against stresses perpendicular to the grain in the latest revision of the Eurocode 5:2022.

I-Beams and Box-Beams

Wood-based I-beams with one or two thin webs (single-web and twin-web I-beams) have the advantage of low weight. The flanges resist bending stresses, and the web provides shear performance. The web must, however, be designed to meet the risk that shear fractures and buckling increase with decreasing thickness of the web.

One way of achieving a shear-rigid web in an I-beam is to make it of cross-laminated sawn timber where the sawn-timber pieces are inclined toward the length direction of the beam. In previously widely used nailed beams (HB-beams, etc.), the web consisted of crossed boards at an angle of 45° to the flanges. Glued webs of sawn timber, where the timber in one or more layers was inclined at an angle of 15° to the flanges, have also occurred in, e.g., the Kämpf, Wolf, and Poppensieker systems [200]. Plywood with a fiber orientation of 45° toward the length direction of the beam gives a web with high shear stiffness and shear strength, but such webs are relatively expensive due to the low utilization of the plywood, i.e., large amount of waste when the web is sawn from standard-dimension plywood. As a rule, plywood web is laid with the fiber direction of the surface veneers in the length direction of the beam.

I-beams and box-beams are designed to carry heavy loads over long distances using less wood, offering a structurally efficient alternative to conventional sawn timber or small-dimension glued-laminated timber. Such beams are designed for use in floor and roof constructions, but they are often used in other applications such as concrete forming.

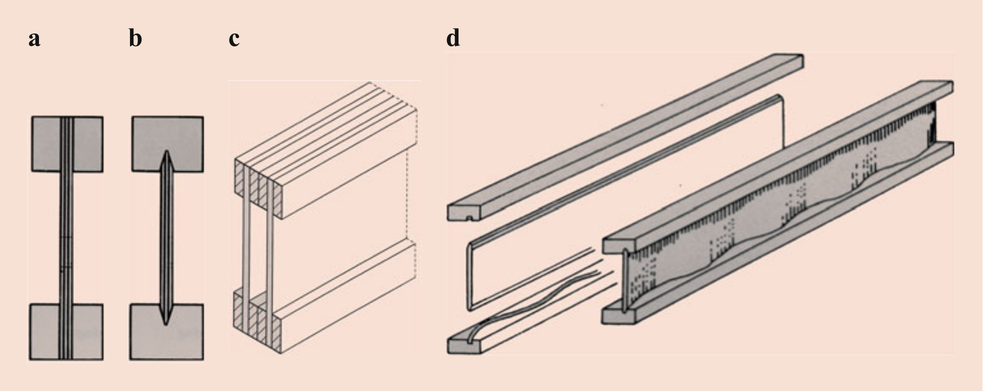
Nowadays, structural I-beams are timber joists with flanges made of strength-graded sawn timber or LVL of various widths, united with one or two webs of various depths made of oriented strand board (OSB), high-density fiberboard (HDF), and plywood or particleboard [8, 201]. In general, the depth (the flange-flange distance) ranges from ca. 200 to 400 mm for I-beams, and up to 1200 mm for box-beams. A length of up to 12 m is common, but longer lengths occur. The flanges and web are bonded together to form an I-shaped cross section. The web is usually glued to the flanges, the most frequently used adhesive being urea-formaldehyde (UF) although melamine-urea-formaldehyde (MUF) and phenol-resorcinol-formaldehyde (PRF) adhesives are also used. Earlier, in, e.g., wood-plywood I-beams, which are fairly common in the on-site construction of beams in the USA, the flanges were glued and nailed on each side of the plywood web, but the web is now normally glued into slots in the top and bottom flanges. To increase the gluing pressure in the bond-line, the slots and the web ends are V-shaped, making the track of the slot undulating in the flanges, so-called sine-wave web joist (Fig. 35.33).

Box-beams usually consist of sawn timber, laminated veneer lumber (LVL), or glued-laminated timber (GLT), flanges with oriented-strand board (OSB), or plywood webs. The hollow cross-section of the beam also permits services to be run in the void inside the member (Fig. 35.34).

Box-girders of solid wood are a type of beam with a function similar to that of a box-beam, but they are less common in use. One type of box-girder produced by the Swiss Lignatur® company is shown in Fig. 35.35. The box elements are made of Norway spruce and have a standard height of 120, 140, 160, 180, 200, 240, 280, or 320 mm, a width of 200 mm, and a length of up to 12 m, although longer lengths are available on request. The weight of a beam is between 7 and 9 kg/m. This type of box-girder is used as beams, purlins, rafters, rafter purlins, supports, webs of I-beams, and ribs for rib plates, and girders are built together to form a flat surface element. The box-girder can be modified to meet fire protection, sound insulation, sound absorption, and heat insulation requirements.

Dried and preplaned Norway spruce lamellae serve as raw material. They are sorted in the sawmill into appearance and strength classes, and production takes place on a commission

Fig. 35.33 An I-beam with: (**a**) flanges glued to a web of plywood (cross-section view), (**b**) a V-shaped track between web and flanges to increase the gluing pressure, (**c**) a twin-web beam, and (**d**) a sine-wave web to increase the gluing pressure



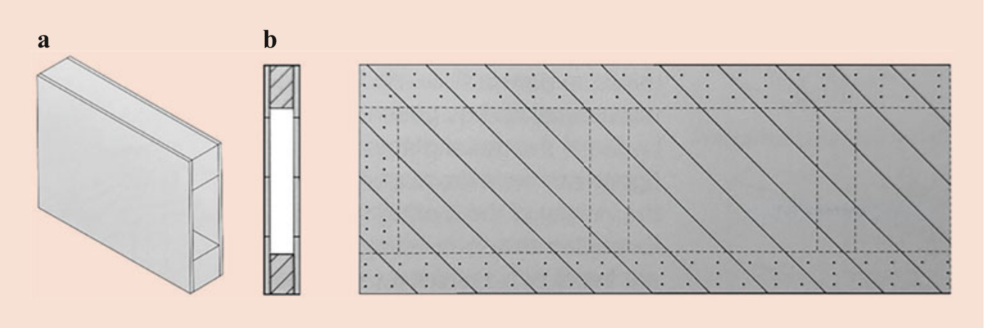
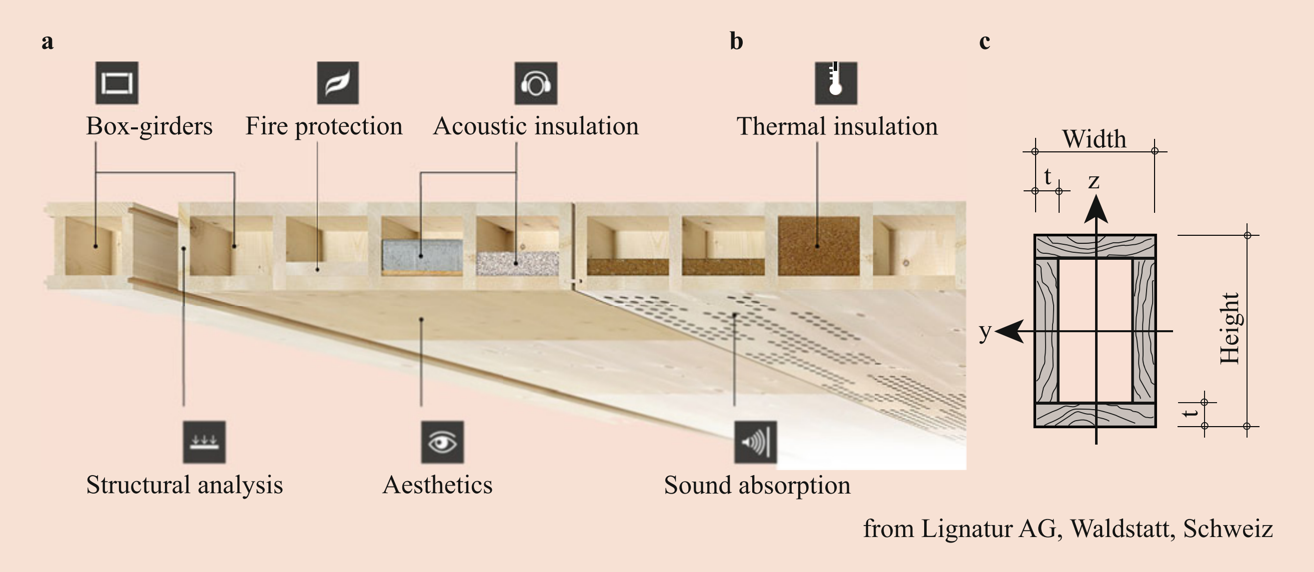


Fig. 35.34 Examples of box-beam design: (**a**) box-beam with webs of plywood, OSB, hardboard, etc., and flanges of sawn timber or LVL, and (**b**) box-beam with webs of nailed boards (cross section and side view)



from Lignatur AG, Waldstatt, Schweiz

Fig. 35.35 Box-girders from the Lignatur™ company: (**a**) a single box-girder element, (**b**), single elements combined to a large-scale surface element modified for acoustics (with acoustic holes or slits), fire protection and thermal insulation, and (**c**), and the cross section of a single box-girder element (**c**)

basis. The lamellae are planed, finger-jointed, assembled, and glued in a so-called high-frequency press. The beams are provided with slits on the side for acoustic purposes, as shown in Fig. 35.35a. Another type of box-girder can be extended in width, and the central hole is filled with insulation, and is used for the easy on-site assembly of plate-shape elements.

Plate-Shaped Elements

Of the many structures and systems provided by different companies, only a few examples of plate-shaped multifunctional wood elements can be given here. The *cross-laminated timber (CLT)* thoroughly described in ▶ Chap. 25 is currently being rapidly developed to give additional multifunctional properties. The *nail-laminated-floor system* (*Brettstapel in German*) consists of vertically layered sawn timber of a defined thickness and width (sawn-timer stacked face-side by face-side) which was initially connected on site by nails. During the last 50 years, the system has developed considerably, and nowadays the sawn timber is joined by wooden dowels or consists of prefabricated elements which are mostly glued together. Additional functions can be provided such as decorative structures or acoustic designs.

In the USA, nail-laminated timber structures have been used for over 150 years as sawn posts and beams with nail-laminated timber floor panels in order to create a robust timber structure [202]. In Europe, nail-laminated timber elements have probably also existed for a long time, but in the 1970s the "Brettstapel" element was successfully developed and promoted by Professor Julius Natterer (1938–2021) as an elaborate timber-engineering system based on nailed-laminated timber. A number of systems based on Natterer's ideas [203] are now commonly used across central Europe, and they are spreading into other regions. The nails in nail-laminated timber make machining operations impossible, and the manufacture of the panels is often by hand and laborious. The nail-laminated technology has therefore been further developed so that wood dowels replace the nails, and diagonal wood dowels replace those perpendicular to the timber to resolve other issues. In the early 1990s, wood-dowel-laminated timber (Dübelholz in German) was developed by Alois Tschopp (Tschopp Holzbau company) with the support of the Pirmin Jung company in Switzerland. They saw this product as being superior to nail-laminated timber as it uses only wood and it is computer numerical control (CNC) machinable, and production of the panel with automated machinery being possible. They proceeded to create the first automated machinery line for dowel-laminated timber. In 2017, the *StructureCraft* company installed the first dowel-laminated timber production plant in North America. A special dowel-CLT system is achieved in which densified wooden dowels are used to join the single sawn-timber pieces. This system is used by, e.g., the Nägeli company in Gais, Switzerland, and the Thoma-Holz company in Goldegg, Austria.

The wooden dowels hold each board side-by-side, forming a stiffer and stronger connection than the nails in nail-laminated timber. In dowel-laminated timber panels, each piece of sawn timber is finger-jointed to full panel length, creating a stiffer and stronger panel than nailed-laminated timber panels as the movements in the butt-joints which are characteristic of nail-laminated timber are eliminated. The next step in the development of the laminated-floor system was to join the sawn timber with an adhesive thereby achieving longer spans (Fig. 35.36). A timber-flooring system is often

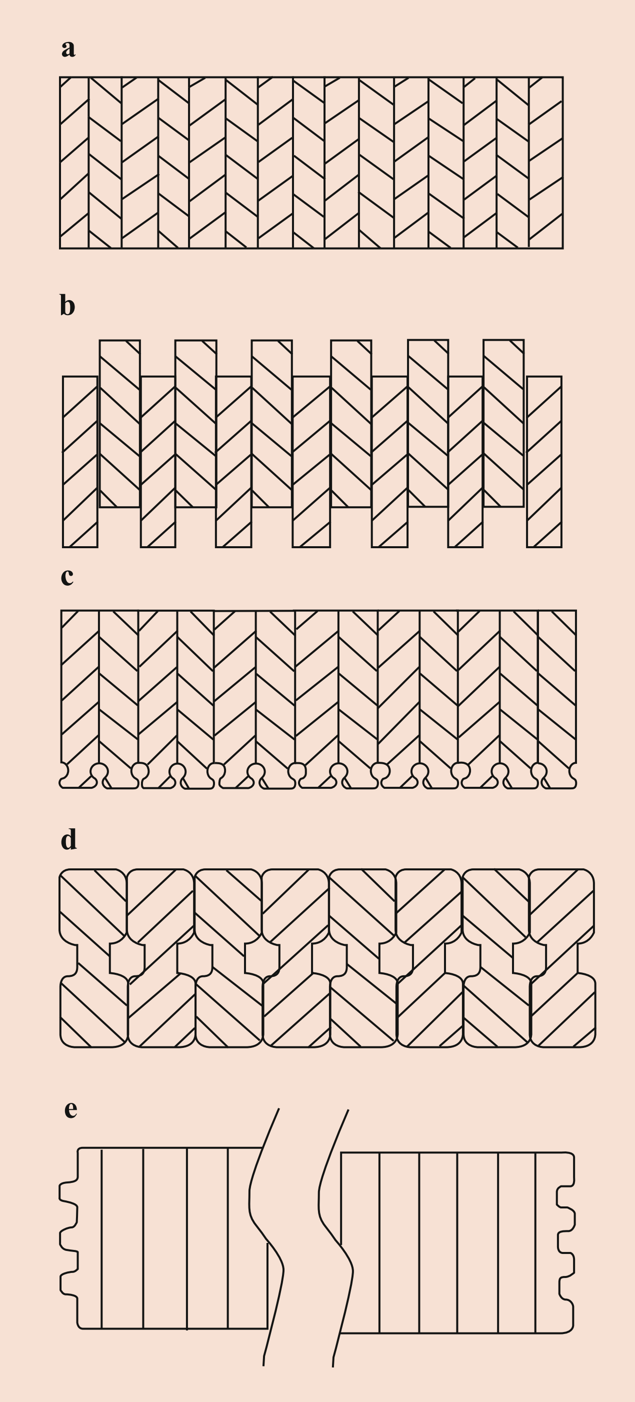


Fig. 35.36 Adhesively bonded or nail-laminated floor system (Brettstapel floor system) – different element structures with different joint formations: Chande numbers (**1**) to (**5**), to (**a**) to (**f**) sharp-edged, (**2**) shifted, (**3**) acoustic design, (**4**) with cable ducts, and (**5**) tongue and groove faces for the tight connection of the elements (for enhanced fire-resistance properties)

combined with a top-layer of concrete to improve the acoustic damping of the construction.

35.3.2 Hybrid Wood Elements

Hybrid wood elements are wood components or elements combined with materials other than wood to achieve additional functions, often creating synergy. Sometimes, also a combination of different wood species or different wood-based materials is referred to as a hybrid. The additional material offers the wood strength and rigidity, protects it from fire, or gives it lightness and transparency. The wood contributes with its low weight and good appearance, and it has ecological advantages. If a load-bearing matrix can be created, wood can be combined like no other material. In many areas, composite constructions such as reinforced glued-laminated timber or wood-concrete composites are already state-of-the-art. Further hybrid materials are being developed and show great potential, and a brief introduction to this field is given here.

The growing demand for innovative applications in the timber construction sector has led to the increased use of high-performing materials commonly used in other fields. The key concept is to combine two or more materials with different characteristics to give a final material with better overall properties than either of the individual constituents. The benefits obtained by merging different materials are being recognized and utilized to overcome design limitations, and to reduce environmental and cost impacts. These materials are not however clearly categorized, so this chapter aims to distinguish clearly between hybrid, composite, and combined materials.

One way of classifying hybrid materials is to distinguish between hybrids on the nano-scale [204] and hybrids on the macroscale [205] as shown in Fig. 35.37:

- Structurally hybridized materials
- Materials hybridized in chemical bond
- Functionally hybridized materials

Wood-Concrete Composites

Wood and concrete are two low-cost load-bearing building materials, where concrete is an excellent material bearing compressive forces, while wood is better in tensile loading. The advantages of a combination of these two materials: The concrete bears loads under pressure while the wood provides reinforcement for tensile load-bearing purposes. Concrete is a mineral and does not burn, and its mass has a positive effect on the dynamic, acoustic, and thermal behavior of the construction, while the wood transmits the tensile forces, insulates, remains visible, and gives the room a pleasant atmosphere. The composite can be created either on-site and as a prefabricated unit. This technology is of particular interest in refurbishment, where new building requirements occasionally result in changes in load conditions, sound and vibrational damping requirements, etc.

Hybrid Flooring Elements Made of Timber and Concrete

Timber-concrete composites are becoming very important in the building-construction sector [206]. Hybrid flooring has many advantages over traditional timber flooring and is now widely used as an effective method of refurbishing existing timber floors and in new multistorey timber-framed buildings [207]. For high loads, large spans, and wherever a particularly rigid construction and a high level of soundproofing and

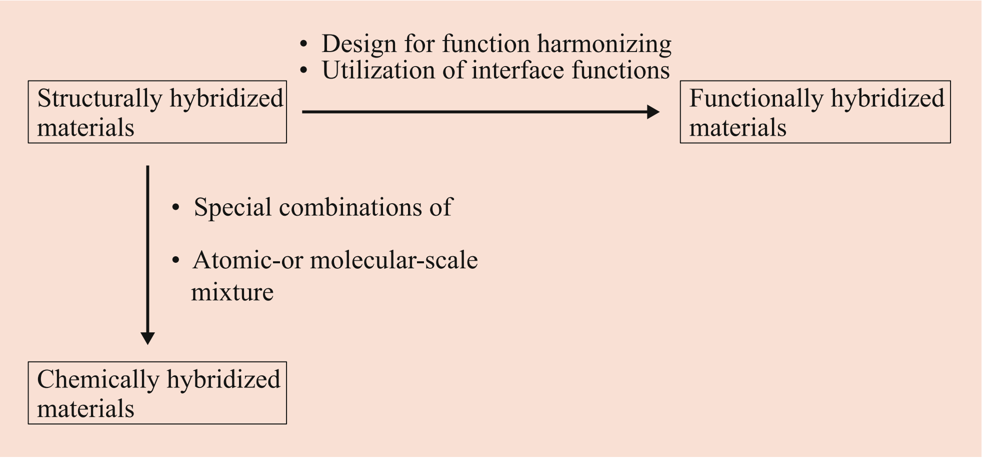


Fig. 35.37 Hybrid materials combine the properties of two (or more) materials, or of one material and space. They include fibrous and particulate composites, foams and lattices, sandwiches, and almost all natural materials. (Based on [205])

fire protection are required, wood-concrete composites offer an interesting economic alternative to pure wood or pure reinforced concrete. These composite materials consist of wooden elements that are connected to a reinforced concrete slab in a shear-proof manner (cf. section "Plate-Shaped Elements"). By placing concrete in the compressive layer of a timber-concrete composite section, it is possible to increase the stiffness, thermal and acoustic insulation, and fire protection of wooden floors, ceilings, and walls while retaining a relatively light-weight and easily recyclable structure. It should also be possible to create slabs with a high-thermal inertia which is becoming more and more important in concrete structures.

A distinction is made between (1) a beam-ceiling construction with a linear supporting structure, and (2) a flat nail-laminated-floor system (dowel-lam), cross-laminated timber (CLT), or the like (Fig. 35.38). The key component of the wood-concrete composite floor is the shear connection between wood and concrete. Two types of shear connection in use are as follows: a shear-force connection directly between wood and concrete and a shear connection using metal fasteners such as screws, anchors, or steel dowels. The shear transmission can also be achieved with the help of notches and dowels or offsets.

The concrete slabs usually have a thickness of 60–160 mm depending on the compressive forces to be transmitted by the overall construction, the fittings to be installed, and the sound insulation requirements.

Wood-Glass Elements

The use of a combination of wood and glass is usually restricted to windows. Interest in glass as a structural material has led to construction methods with a load-bearing and stiffening function, often accompanied by filigree steel parts in order to preserve the transparency of the glazed structure.

Wood is less strong and less stiff than steel, and this leads to larger dimensions in the cross-section and, consequently, less transparency. Nevertheless, wood-glass composites enjoy a high level of acceptance because of their esthetic quality, and they have a great structural potential for further development.

Glass and wood are brittle materials and can be expected to behave accordingly when combined, but contrary to expectations, experimental studies have shown that the load-bearing capacity can be further increased even after the first cracks have appeared. This postbreakage behavior is a load-bearing reserve. Ceiling beams in a wood-glass composite structure were used for the first time in the Hotel Palafitte at Lake Neuchâtel, Switzerland. The composite cross-section consists of a pane of glass that withstands the shear forces and is reinforced at the sides with glued-on softwood timber to stiffen and take over the pressure and tensile forces.

Combining wood and glass to achieve an appropriate load-bearing composite element is a challenging task since it involves two materials with very different physical characteristics. Due to its fibrous structure, wood can withstand tension while the glass resists compressive forces well, showing a tendency to break when the forces reach certain limits. Together, the materials complement each other: under large loads, where the wood tends to deform plastically until it fails completely, maintaining a certain load-bearing capacity for a certain time [208, 209]. The engineered wood-glass combination panel can also be an ecological alternative to aluminum-based façade systems thanks to the environmental performance of wood. This is clearly demonstrated by a comparative life-cycle assessment (LCA) analysis, although the product is still not widely used in the building sector.

The term "timber-glass composite" (TGC) has been used in scientific articles and research reports to describe an innovative façade product [209], meaning a composition of timber and glass, but it is in fact not a composition but a combination of two different materials. For this reason, a new term was introduced and the term "engineered wood-

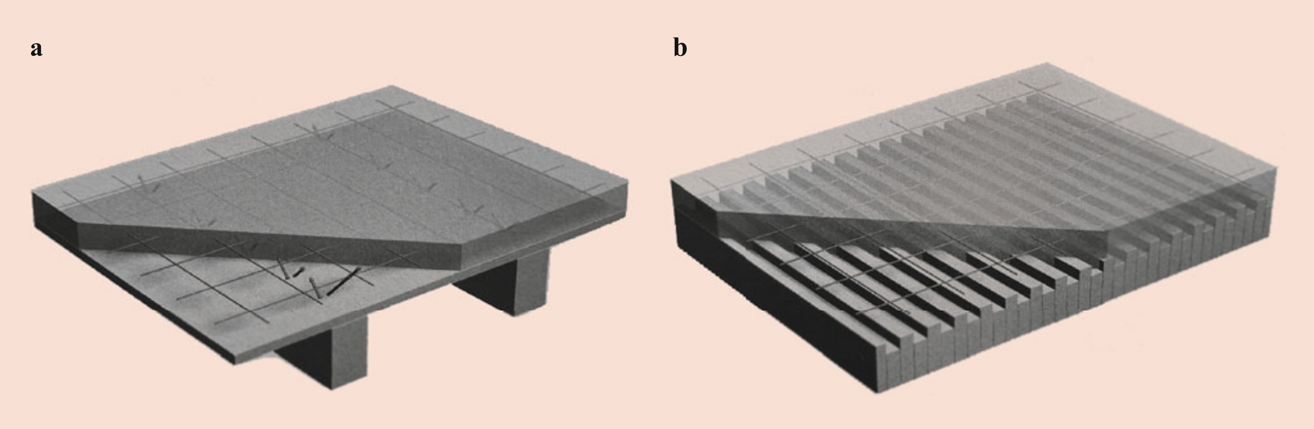


Fig. 35.38 A beam-ceiling construction with a linear supporting structure (**a**), and a flat nail-laminated-floor support system (**b**)

glass combination" (EWGC) has been considered to be more appropriate. The basic concept is that these engineered wood-based elements merge the characteristics of materials, different species of wood, or cross-sections of the trunk or timber and glass, in a unique way. The size of the constituents of an engineered combination is greater than the size of a hybrid or composite material when the different components such as wooden boards and glazing panes are glued or screwed together. Engineered wood-glass combinations combine the stiffness and ductility of wood and glass, avoiding fragility and deformability.

In comparison with fossil-based building materials, biobased materials such as wood have a low-environmental impact, capable as a tree of absorbing CO_2 from the atmosphere and storing carbon in the wood tissue, requiring low energy for processes due to its low density, and being easily recyclable, and the excellent properties of wood as a material with very low-thermal conductivity increase its applicability for the façade-interface between inside and outside. The presence of natural sunlight enhances the health and habits of people living and working inside buildings, and an increase in the area of the transparent envelope is the best way to provide solar heat energy and lower the energy required for heating during the winter. Transmission losses through the building envelope and possible solar gains through the glazing must be calculated in order to determine the optimal size of the glazed area and to enable a suitable selection of glass type [210]. An engineered wood-glass combination thus has a potential as an ecological alternative to a conventional aluminum façade. Its advantageous properties include the transparency, stiffness, and strength of glass and the ductile nature of the timber under compression. By combining these materials with suitable structural adhesives, the brittleness which is the main drawback of glass can be avoided [211].

The first examples of wood-glass combinations were presented in the mid and late 1990s by several German workers [212, 213] who considered gluing glass into wooden frames, and these were followed by specific studies regarding load-bearing engineered wood-glass combination products such as I-beams and shear walls [214]. In wood-glass I-beams, a glass web carries the external load and makes a large contribution to the bending stiffness while the wooden flanges serve as reinforcement of the glass web and, if properly designed, contribute considerably to the ductility of the beam [211, 215].

The first tests regarding shear walls were carried out by Edl in 2008 and later by Hochhauser [216]. Four-point-loaded wood-glass shear walls show that the glass elements act as shear elements with compression diagonals [216], and the stiffness of adhesive used, whether deformable adhesive based on silicone and acrylic or a more stiff adhesive, considerably influences the deformation behavior of the shear-wall [217, 218]. The fire performance of an engineered wood glass combination is currently in focus.

A window acts as an interphase between the indoor and outdoor environment of a building, and it has a long tradition as a wood-frame-glass element. In recent decades, the wood-frame has been developed into a multilayer and multimaterial compound, mostly with the wood layer on the interior and the aluminum layer on the exterior. In order to improve thermal insulation, new glass-systems (insulation glass, vacuum glass) have been driving forces in the design of new windows and window frames. The latest innovation is a fairly thin vacuum glazing with a high thermal-insulation capacity, which may change the design of window frames in the near future [219]. The vacuum glasses have an overall glass thickness of 6–8 mm with an intermediate thin layer of about 0.8 mm vacuum. This construction provides an insulation value of the glass (U_g) of 0.4–0.7 W/m^{2}K and has a mass per unit area of about 15 kg/m^2. This is 30–50% less weight than that of a comparable conventional triple-layer insulation glass.

35.3.3 Light-Weight Elements

The main benefit of the light-weight materials in furniture applications, caravan construction, etc. is their high strength-to-density ratio. A low weight is advantageous in the transport and handling of products, and it also lowers the transportation costs. Light-weight structural materials based on wood and paper layers are being increasingly considered as substitutes for commonly used materials such as fiberboards or particleboards. Light-weight materials can be divided according to their functions and structures into three groups: (1) light-weight materials which combine materials with a low weight-to-strength/stiffness ratio, (2) light-weight materials which are used mainly for structural purposes that, with a minimum of weight, can distribute applied loads, and (3) light-weight systems providing not only a supporting function but also thermal insulation, etc. (cf. Fig. 35.35). There are two main streams of light-weight materials with different purposes: resource optimization to reduce material usage with maintained performance and function and high-performance materials for advanced uses in, e.g., vehicle construction where a low weight is in focus.

A sandwich panel is a structure made of three or more layers having a low-density core and a thin high-density facing layer bonded on each side [220]. Sandwich panels are used in situations where high-structural rigidity and low weight are required in, e.g., aircraft construction and naval interior design. In the furniture industry, light-weight constructions have become increasingly popular [221], but one of the main challenges is to find appropriate connectors, as common screws and bolts are not sufficiently anchored in the core layer.

Sandwich panels, with a core of an insulating material, kraft-paper honeycomb (Fig. 35.39), polystyrene, polyester, balsa, wood-fiber, etc. between outer sheets of a board material such as plywood, OSB, MDF, HDF, or other type of wood-based laminate, exist in a broad variety with special designs for different purposes such as high strength, fire resistance, and low acoustic or thermal transmission or give an esthetic appearance to furniture or interior joinery. The honeycomb concept goes back a long time, but its first major breakthrough came around 1945. Pflug et al. [222] present a survey of continuously produced paper honeycomb sandwich panels for furniture and provide a sandwich selection chart for design processes.

The honeycomb design provides a low-cost industrial production concept. In general, expanded honeycombs are made of a low-cost recycled paper grade known as testliner. Adhesive strings are first printed on the paper which may come from one or several reels. Second, a stack of several sheets are bonded together. Those sheets can be cut into strips prior to or after stacking. In the third stage, many stacks are bonded together, giving an unexpanded endless paper honeycomb before the sheets are finally pulled apart, expanding the stack into a hexagonal honeycomb core. The residual stresses in the paper honeycombs are relaxed after expansion by controlled heating. Different processes and different core structures may be processed and applied in sandwich structures. A comprehensive and concise compilation of the different technologies, designs, materials, and manufacturing techniques is provided by Bitzer [223] and Vinson [224].

Fig. 35.39 Sandwich element with kraft paper honeycomb structure. (Photo D. Sandberg)

Honeycomb sandwich structures combine flexural rigidity and high bending strength with low weight, and they are playing an increasing role in wood-based and paper-board-based developments. The sandwich structure is not a single material with unique mechanical properties but rather a structure the design of which must be adapted to suit the particular uses to which it will be subjected. The basic concept is to use thin, dense, strong facing materials bonded to a fairly thick, light-weight core. Each component is itself relatively weak and flexible, but in combination with each other they provide an extremely stiff, strong, and light-weight structure where the facings withstand the bending load and the core withstands the shear load. Sandwich structures are applied in a broad range of applications in door-panels, furniture, and packaging (Fig. 35.40).

Barbu [225] presents a comprehensive survey of light-weight wood composites incorporating foaming agents, multilayered panels with light-weight wood species (e.g., balsa), or sophisticated honeycomb cores for the middle layer. Shalbafan et al. [226] describe the light-weight panel production of foamed particleboards, where foaming agents are expanded in the production process to reduce the core material density. Déneši et al. [227] describe the production of fiberboard with symmetrically distributed densities in a

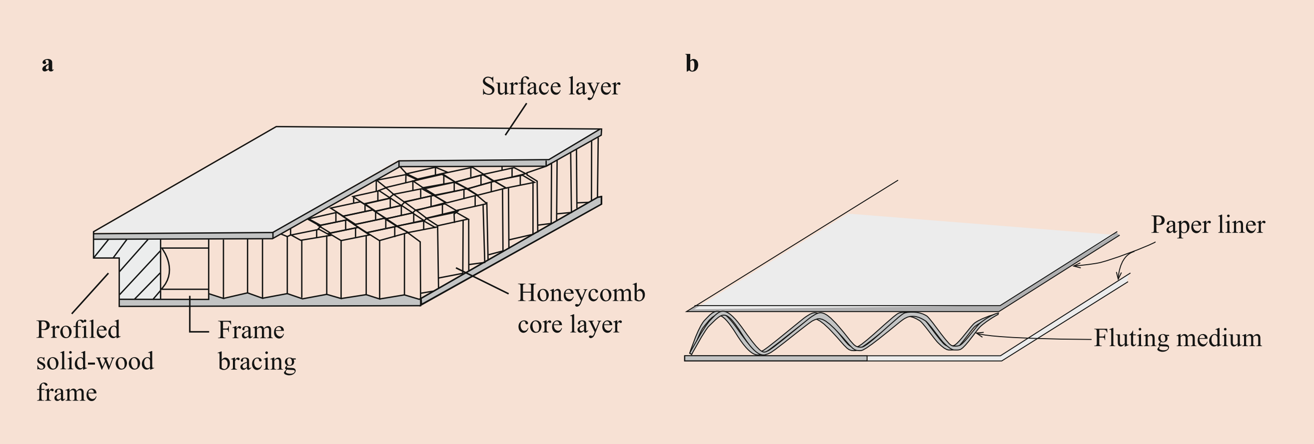


Fig. 35.40 Example of wood- and paperboard-based sandwich structures: door panel (**a**), corrugated board (**b**)

sandwich-like board structure. Another approach has been to use of foamed lignin as a core-layer material [228].

Several ideas for light-weight panels of solid wood that combine low weight with high strength have been presented, particularly for buildings and other structural systems where they have many advantages, i.e., a high strength-to-weight ratio, a low framework cost, and good thermal and sound insulation properties [229]. Dendrolight® is a panel that consists of a core layer of cross-aligned boards with longitudinal kerfs (Fig. 35.41) glued to the surface layer at an angle of 45° [230, 231]. Skuratov [232] presented a three-layer-panel with a core of low-grade sawn timber with a pattern of hollow cells which reduce its weight. Nilsson et al. [233–235] presented a type of light-weight panel, cross-laminated in three layers and of solid wood throughout, the weight being reduced by the hollow middle-layer. It is possible to optimize the properties by mixing species in the panel, e.g., a high-quality and high-density wood on the surface and a low-quality wood with low weight in the core, while at the same time keeping the costs down (Fig. 35.41). The panels are assembled with wooden dowels.

The main motivation for wood-based composites has been the need to compensate for the heterogeneity and anisotropy of solid wood, producing large-panel dimensions with a good surface at a low cost and thus a cheaper product than high-quality sawn timber. Particleboard is no exception, and it has been developed into a great variety of different products, especially as a base for furniture production and interior use. The production process is in general optimized for wood as the main raw material, but other biobased and plastic materials have been used. There is a demand for large amounts of cheap wood as raw material. For furniture, the strength of the board is not usually a major issue, and the traditional way of reducing weight is to produce a three-layered particleboard with a low-density wood-particle core. The core can sometimes be strengthened by higher density regions aimed for connections, etc., which requires careful planning related to how the panel will be used in the final product.

Wood-particle-based materials of low density can also be made by using light materials other than wood in the core (cf. ▶ Chap. 27). In the Kaurit Light panel® from BASF company, expanded polystyrene (styrofoam) is mixed with the wood particles in the core layer. The saving in weight is up to 30%, and both adhesive and wood can also be saved. Other particleboard products in the same category are AirMaxx® (Nolte company) and BalanceBoard® (Pfleiderer company) where a weight reduction of up to 30% is achieved with a core layer of a biomass granulate based on rapidly regenerating annual plants (see ▶ Chap. 27). The Unilin company has developed a very light-weight particleboard *Air 400 Light* with a medium density of 430 kg/m^3.

Fast-rotation plantation trees and various species of grass, bast, leaves, fruits, seeds, or other agricultural plants can provide biobased fibers for either light-weight or "normal-weight" particleboards. The main difference between wood and many other biobased fibers is the higher content of cellulose, hemicelluloses, and lignin content in wood, but the fiber length may also differ, and this may influence the mechanical properties of the final board. Biobased fibers that are already in use include agave, bagasse, bamboo, barley straw, cotton stalks, flax shives, hemp shives, hop, kenaf, maize stalks, melaleuca, miscanthus, nettle stalks, oat husk, rape straw, rice straw/hulls, ramie, seagrass, sisal hemp, sunflower stalks, topinambur, waterlily, and wheat straw. For further reading, see ▶ Chap. 30.

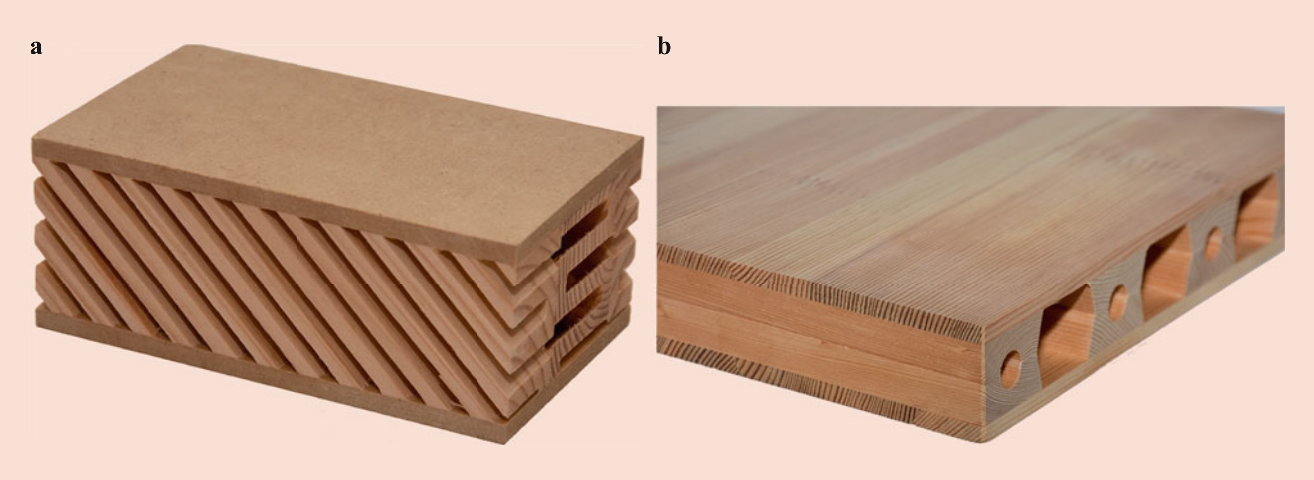


Fig. 35.41 Sophisticated middle layer structures in solid wood lightweight panels: Dendrolight® (**a**), and a three-layer cross-laminated panel (**b**). (Photo D. Sandberg)

35.3.4 Acoustic Elements

Acoustical engineering in buildings involves a wide range of designs and building structures related to noise, sound, and vibrations, where noise reduction (residential neighborhoods) and sound improvement (e.g., concert halls) are a major priority. In general, acoustical engineering assesses the noise impact of the construction, where the term “noise” refers to unwanted sound or low-frequency vibrations which are considered unpleasant, loud, or disruptive to hearing or feeling. From a physics standpoint, noise is indistinguishable from sound, as both are vibrations through a medium such as air, a solid, or a liquid. The difference arises when the human brain receives and perceives a sound as unwanted noise. In general, “noise” is considered to be a disturbance to desired “signal.”

Wood and wood-based building materials, indoor furniture, and other products contribute to the acoustic environment. The basic acoustic properties of wood as a material are discussed in ► Chap. 6. This section touches only a few selected aspects and material engineering approaches to control the sound impact in an indoor environment. Acoustic comfort can be defined as the well-being and feeling of a building or house occupant regarding the acoustic environment (noise-producing transport, equipment, activity, and neighborhood). Providing acoustic comfort requires minimizing intruding noise and maintaining satisfaction among residents at home and in offices, schools, hospitals, workshops, etc. Every acoustic consideration involves sources, paths, and receivers of sound [236]. In order to control sound in a building environment, engineered acoustic elements may focus on the following:

- Impact noise damping
- Sound attenuation
- Sound absorption including reverberation in rooms

Wood provides many different concepts to meet one or more of these acoustic occurrences (cf. Fig. 35.35). Low-density fiberboards, particleboards, and light-weight elements are often used for sound insolation. Cork is used under flooring to reduce the impact noise caused by, e.g., walking.

Acoustic Wood Material for Furniture and Indoor Design

Since furniture is a considerable part of the indoor environment, it also contributes to the acoustic comfort, especially in facilities such as restaurants, schools, and kindergartens, where the acoustic comfort can be increased by adapting bench and table top surfaces which reduce the sound-wave reflection. It is also possible to design the shape of the furniture to improve acoustic comfort. Acoustical importance is being increasingly attached to the furniture itself because, due to the glass, metal, and concrete often used in the building, every acoustic improvement is helpful. Replacing sound-absorbing cabinet fronts with sound-absorbing cabinet fronts noticeably increases the sense of well-being in the room.

The German EGGER company and the Swiss NH Akustik + Design company produce and market wood-based acoustic panels for ceilings, furniture, wall cladding, and rigid and mobile partition walls or high-quality interior constructions. The panels are a laminate consisting of a core panel, an acoustic fleece, and a perforated decorative surface. Veneer-based acoustic panels combining interesting design features are also available on the market, combining sound-absorbing and decorative aspects in standard and light-weight structures. The surfaces are incised with holes for sound absorption. The holes are 0.5–12 mm in diameter, and they cover the surface in a linear grid system with typically a distance of 1.5–12 mm between the holes to give different acoustic damping properties. Key features of acoustic elements are that they give acoustic comfort while being light in weight and easily integrated furniture and interior design.

35.3.5 Thermal-Insulation Elements

Thermal insulation is an important component of modern homes and other buildings, providing the comfort required for ease of living and paying for itself in fuel savings during winter heating and summer cooling. A large variety of thermal-insulation elements are available on the market, mainly not only for timber-engineering purposes but also for components like windows (cf. Fig. 35.35).

35.3.6 Other Niche Products

Wood-based products are used in many “niche” products for the automotive sector, for boat industry, sport goods, and in wind-power energy systems (towers, rotor blades), but wood-based materials often have specific functions in, e.g., furniture and interior applications.

Sculptural and Flexible EWPs

Sculptural EWPs are solid wood or EWPs where the surface has been machined, embossed, molded, or patterned to achieve an esthetic appearance [13, 14], and the esthetic performance may be combined with a machining to make the EWP flexible. The products are used mainly for interior design, but they are also used for the decoration of decking, cladding, parquet, log homes, facade boards, or panels’ exclusive constructions. A large variety of surface appearance can be achieved, and they can be strengthened by suitable surface treatments (Fig. 35.42).

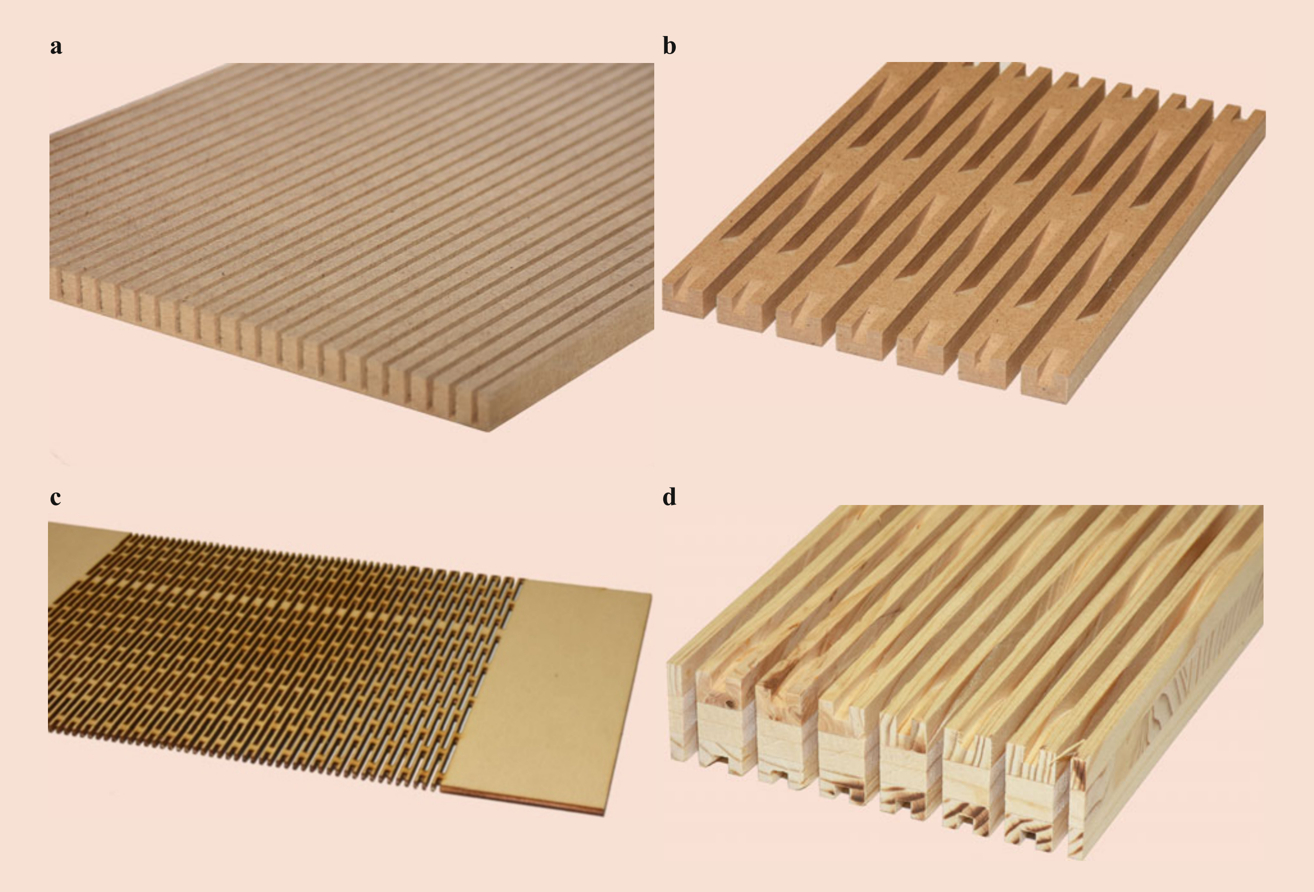


Fig. 35.42 Examples of flexible panel materials for interior use: (**a**) grooved MDF for increased bendability, (**b**) sculptural MDF which slightly increased the bendability, (**c**) flexible and sculptural plywood, and (**d**) a flexible panel of solid wood (Photo D. Sandberg)

Fig. 35.43 Recoflex® elastic particleboard made of wood, cork, and latex granulate bonded by a polyurethane-based adhesive

The elastic particleboard Recoflex® from the German Berleburger Schaumstoffwerk (BSW) is a combination of wood, cork, and latex granulate, bonded by a polyurethane-based adhesive (Fig. 35.43). The elasticity of the board is achieved by the polyurethane and latex elastomers, the porous structure and low density of the material, the dimensions of the granulates, and the random, homogeneous structure. The combination of wood and elastomers has created a material whose elasticity and strength properties make it suitable for light-weight molded products for furniture production, interior fittings, and flooring systems where the material provides sound insulation and gives the floor a lower modulus of elasticity. The density of the board is approximately 450 kg/m^3.

Shock Absorbance

Engineered wood composites are being developed for load-bearing and shock-absorbing applications in the automotive sector, where high reliability, low variation, and high reproducibility are important factors. Extensive material data, material simulation, and component simulation with respect to crash tests are important factors when developing a material chart, as described by Müller et al. [237]. Reliable data are needed for the first material selection and subsequent crash simulations, for acknowledgment by the development engineers in the automotive sector [238].

Key features for the automotive sector are extensive material and component data for crash simulation tests, high reliability of materials and components, computer-aided engineering models of materials exposed to dynamic and static loads, and cost efficiency.

A special application based on the shock resistance of wood and wood elements is in timber guardrails for highway applications as developed by van de Kuilen et al. [239–241], where the main task was the reduction of zinc emissions from steel barriers.

Wood in Sporting Goods

The equipment required for sporting purposes, including tools, materials, apparel, and gear, varies depending on the sport. Nearly every sport uses or has used some sort of wooden implement, and the use of wood is often advanced and of great added value. Many items of sporting goods combine wood and other materials such as aluminum, carbon-fiber composites, glass, steel, and a variety of polymers.

Some sports use solid pieces of wood, and others use advanced composites requiring special manufacturing techniques. Baseball bats are made from a variety of woods like ash, hickory, and maple, each with its own specific characteristics. Ash and hickory are tough tree species traditionally used in many sporting goods, but hickory has fallen out of favor due to its weight, despite its being the strongest wood available. Maple is strong but can shatter when the wrong piece of wood is use, and bamboo is becoming popular due to its combination of strength and light-weight. Cricket bats are made of white willow, which is tough, does not dent easily, and is light in weight.

Ice-hockey sticks were previously always of wood, but fiberglass and aluminum have become more common, although wood is still used for cost reasons. Typically, a hockey stick used several types of wood laminated together. Polo mallets used to be made of a palm "wood," but composite materials are used nowadays. Lacrosse sticks were made of hickory, but this has been replaced by more modern materials.

Some sports use wood in another context. Football goal posts used to be made of wood, but they are now often made of aluminum. The same is true for rugby. Various track and field events previously used wood for events such as hurdling and the pole vault, but these have been replaced with metal, plastic, or composite materials. Indoors, wood is still the ideal playing surface. Basketball is played mostly on courts made of maple wood. Bowling alleys are typically made of maple or pine. Handball, racquetball, squash, and volleyball are played on courts similar to the basketball courts.

Wood is still vital in other sports. Pool cues are made of maple and snooker cues of ash. Maple is stiffer and is cheaper, but some hand-crafted wooden pool cues are incredible works of art. Archery bows were typically made of yew although composite materials have become more popular in modern times. Archery longbows are still manufactured from laminated wood with a range of species including hickory, lemonwood, maple, and yew for the belly, core, accent, and back element of the bow. Surfboards used to be made of wood like redwood or balsa wood, but they are now made of lighter materials like fiberglass. Wooden surfboards are still popular with some surfers, and balsa wood is making a comeback due to its lightness and strength. Skateboards are typically made from either birch or maple (sugar maple is considered to be the best available on the market), but bamboo is also used. Skis are a utility tool, and sporting goods have been made of wood for thousands of years, where skilled makers have selected wood and production processes to adopt to local conditions and type of snow [242, 243]. The construction of modern wooden ski cores is described in the next section.

35.4 Engineered Wood Systems

An "engineered wood system" is a wood-based product designed for a single function or purpose. This is in general a product existing on the market, marketed for its "system-function" rather than because it is made of wood, and it may thus not be easy to distinguish between an engineered wood system and normal use of timber. Therefore, this section gives examples of three such systems:

- Wood-composite skis
- A formwork system
- The click-flooring system

35.4.1 Ski Cores

The ski core is an important part of a ski, because it determines the character of the ski and its flexibility. Various wood-based core types are used consisting of wood species such as ash, aspen, paulownia, and sugar maple. Each species of wood is used for a specific purpose, and the choice of species depends on the type of ski to be developed. A typical wood combination is European ash and European maple in the core and in the outer perimeter of the ski. This provides a strong frame that smoothens and dampens the ride [244]. High-density maple is also used to create a solid core in the ski, either aspen or paulownia, both very light-weight hardwoods, being used in the rest of the ski. The combination of these different woods creates a strong, damp, light-weight core which gives the ski its specific character (Fig. 35.44). The performance requirements depend on whether the ski is intended for free riding, racing, common piste skiing, Nordic skiing, etc.

It is a special challenge to design light but mechanically adequate Nordic ski cores, as outlined in Fig. 35.45. Most Nordic ski cores consist of a honeycomb or chamber structure.

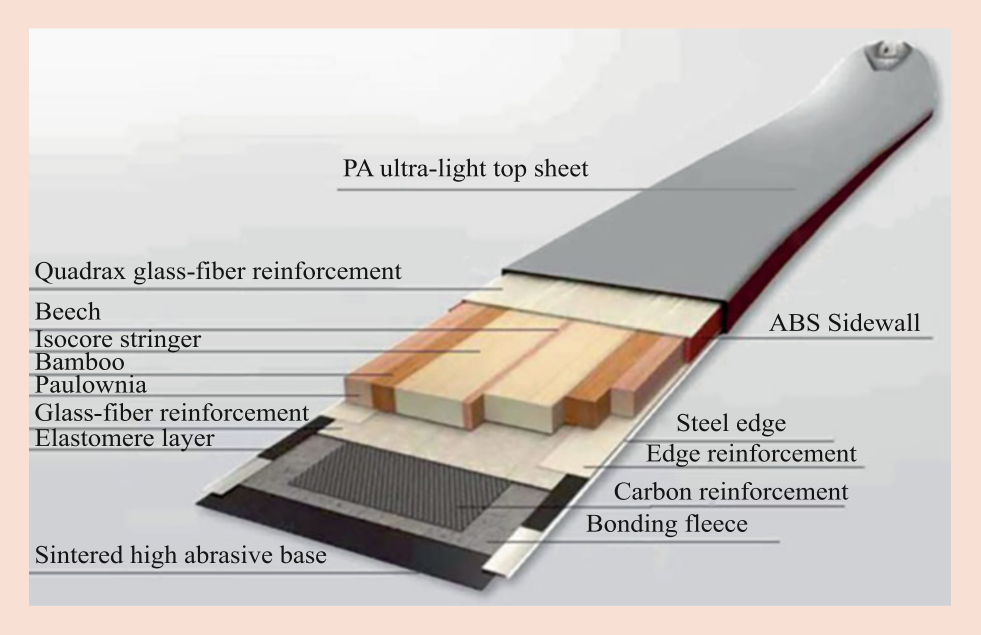


Fig. 35.44 Example of a construction system for an alpine ski with a sophisticated wooden ski core produced by Dynafit company PA - polyamide, ABS - acrylonitrile butadiene styrene. (Permission Dynafit)

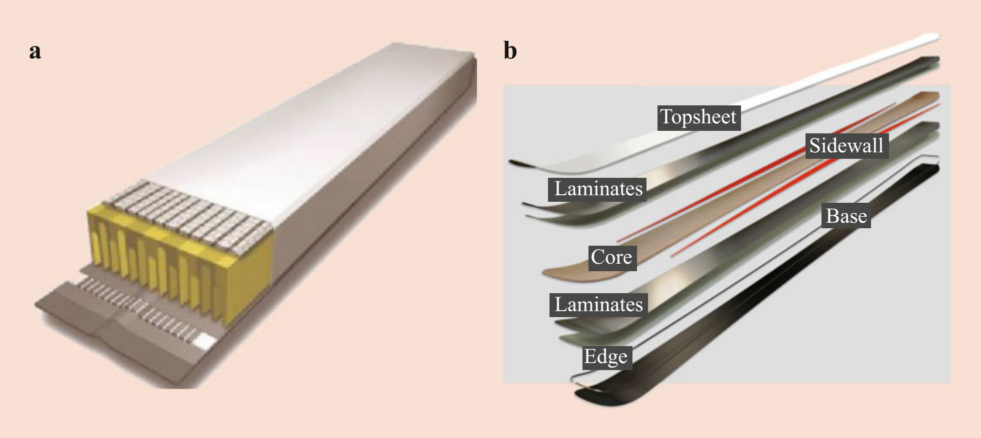


Fig. 35.45 Ski design with a light-weight wooden core construction (yellow), Air Tec Technology, Fischer company (**a**) and a conventional alpine ski from Atomic company (**b**)

35.4.2 Formwork (Shuttering) Systems

Two examples of companies making formwork systems are the Austrian DOKA company and the German PERI company. In both cases, the companies' business idea is to support construction projects with engineering knowledge and formwork systems in all fields of the construction sector. The formwork products, systems, and service include, e.g., formwork panels, wall formwork, climbing formwork, tunnel formwork, bridge formwork, and tie systems together with field support, software, and training. Formwork systems are often based on sophisticated wood-based I-beams, of which the DOKA-system is an example.

DOKA® is a formwork system for concrete construction, with the successful strategy of reducing the total construction costs for the customer by achieving a high-quality result in concrete casting at the building site with a smooth forming operation and no costly downtime (Fig. 35.46). The DOKA system is supported by an in-house construction and logistics system to provide a single source for products, services, planning, and project management details. After the DOKA formwork has been used at the construction site, the components are transferred into an advanced "recycling system" for cleaning and renovation before being used by the next customer.

The DOKA company has an interesting and long history, starting when the carpenter Stefan Hopferwieser was granted a concession to conduct the carpentry trade in Kollmitzberg, near Amstetten in Austria. In 1869, he moves to Amstetten and used the new location to expand his sawmill and

Fig. 35.46 The DOKA formwork system. The vertical standing I-beams (formwork beams) are the main wood-based element in the system

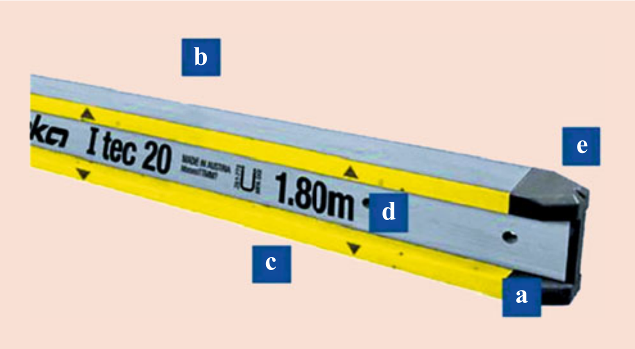


Fig. 35.47 Engineered high-performance formwork beam with strength-graded Norway spruce flanges, birch plywood web, and a plastic protection sheet on the wide faces of the wooden flange and a plastic beam-end protection (Courtesy of DOKA). a – polyurethane beam-end protection; b – an I-tec protection sheet; c – marking raster; d – system holes; and e – notch at the beam-end protection cap

carpentry operations into the globally operating formwork company known by the brand name DOKA since 1956.

The DOKA Formwork Beam

DOKA® timber formwork beams are made of wood and are intended for use in floor and wall formwork (Fig. 35.47). Timber formwork beams are approved only for loads imposed by direct support in concrete construction, not for heavy point loads in conjunction with wide spans (e.g., holding girders). A formwork system is intended to be used several times, and a high-performance formwork beam thus has to be easily assembled and disassembled. The marked modular grid, the system holes, and notches facilitate assembly and disassembly, and the beam-end and flange structure protect the beam from damage. DOKA® formwork beams contain no wood preservatives, and reprocessing by incineration in a suitable incineration plant is recommended, not in an open fire or domestic wood burner.

The basic design concept for these beams includes a solid-web beam made of wood and wood-based materials with Norway spruce for the flanges, automatically machine-graded, tested by the tensile-loading method, a web of special flat compressed particleboard or three-ply birch plywood, a polyurethane end reinforcement, and two system holes at each beam end.

35.4.3 The Mechanical Locking Parquet-Flooring System

EWPs can also be designed to be decorative rather than for specific constructive properties. Parquet flooring is a good example of an EWP where the decorative design and appeal are an important feature. According to the European Parquet Federation, parquet production in Europe in 2016 was more than 80 million square meters. The parquet industry is an important producer of high-value wood-based products based largely on hardwood species.

The engineering process includes the composition of a prefabricated parquet-flooring element such as a multilayer built up, the material of the top layer including decorative design and appeal, the support layers, and the surface finish. The narrow faces of the elements must have a tongue-and-groove-interlocking system (Fig. 35.48) or an interlocking system to connect the elements in a flooring assembly (Fig. 35.49). The surface must have a good scratch and abrasion resistance, and the floor should give an impression of smoothness and warmth. Further requirements are impact sound insulation, slip resistance, resistance to fire, etc. which

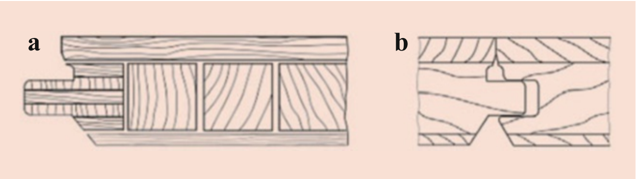


Fig. 35.48 Typical parquet system with tongue and groove. The geometry with gaps between adjacent middle and bottom layers allows a tight alignment of the top layer: (**a**) front end connection with glued-in plywood strip, and (**b**) length-side connection

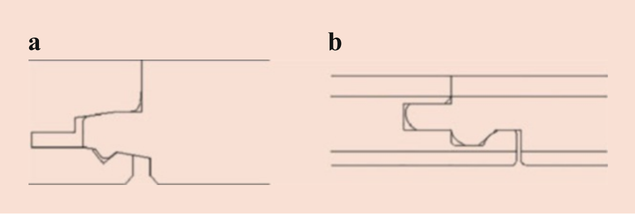


Fig. 35.49 Typical worked edges with a mechanical locking system for flooring. The drawings show two different "click-process" systems developing a tension force in order to stick the units tightly together at the top layer: (**a**) the principle of the locking system, and (**b**) a locking systems made in one piece with the core of different material than top and back layers [250]

all have to be within the frame conditions of the relevant standards, which, at least in Europe, are also related to applicable building regulations. Parquet flooring is a challenging set of engineering tasks involving technical, human comfort, and economic issues.

The Perstorp company in Sweden is recognized as the inventor of laminate flooring in 1979 (Pergo®) based on an advanced decorative surface laminate applied to a layer of wood-based material. Other companies followed this idea, and laminate flooring was further improved with respect to production technology, e.g., manufacture of direct pressure laminate, improved wear resistance according the European standard EN 13329) [245], and improved water repellence at the edges of the flooring panels. The invention of the mechanical click-locking system led to a new generation of laminate panels, where laminate floor planks were installed at the building site. Mechanical locking systems for laminated floor panels (Alloc System and Unilin/Uniclic locking technology) were introduced in the mid-1990s by the Välinge Innovation company in Sweden. Most of the innovative steps have been patented [cf. 246]. The click system made it necessary to adapt the core material which was increasingly made of an MDF/HDF substrate which became thinner and cheaper.

The mechanical locking system completely changed the flooring assembly, at the building site, and subsequently became commonly used in multilayer solid-wood parquet systems (Fig. 35.49). The Swedish inventor and entrepreneur Darko Pervan and his company Välinge Innovation further developed the mechanical locking system with a number of patents.

Advanced fold-down locking systems, bevels, surface structures, and innovative production methods were successfully introduced to the flooring industry providing worldwide services covering the complete range of materials such as laminates, solid wood, engineered wood, and resilient products such as stone-plastic composites (SPCs), luxury vinyl tiles (LVTs), and wood-plastic composites (WPCs).

According to the current versions of the European standards EN 13329 [245] and EN 13756 [247], there are several types of wood-based flooring coverings:

- Parquet: wood-flooring system consisting of a top layer of solid wood with a thickness of at least 2.5 mm with or without additional layers, whereas in a multilayer system wood-based material must be at least 75% of the mass
- Veneer floor covering: similar to parquet with no minimum thickness for the top layer
- Laminated-floor covering: rigid multiple-layer flooring with a décor surface, a substrate and backer, and worked edges. Various wood-based materials are used as substrate of the core middle layer. The upper decorative layer, which may vary in texture and gloss, consists of one or more sheets of paper impregnated with an aminoplastic thermosetting resin

The wood-flooring products are defined and characterized (including appearance classes) and are listed in EN 14342 [248], which states how the conformity is to be evaluated and the requirements for marking wood-flooring products. The various requirements relate to dimensional characteristics, reaction to fire, release of dangerous substances, breaking strength, slip resistance, thermal properties, etc. EN 13329 [245] includes specification and requirements for laminate floor coverings and provides a classification system to indicate where laminate floor coverings will give satisfactory service.

Kisseloff [249] describes modern parquet manufacturing systems, and Kruse et al. [250] provide a general survey of the various parquet types as well as installation principles production concepts. Gronalt et al. [251] describe a system of mass-customization in the parquet industry focused on aligning natural features of the face layers of parquet strips.

Key features are resource efficiency for the top layer and the use of low-quality material as middle layer, multilayer composition including functional layers (e.g., sound-proof layers) when requested, a sophisticated mechanical locking system for easy on-site laying, reduced swelling, and shrinkage due to cross-layered composition, and prefabrication including surface coating and sophisticated water-repellent measures at the edges, etc.

The click technology is also used in furniture and interior construction for the connection of panel parts without additional fittings or adhesives. The Egger company has developed a furniture component click system (Fig. 35.50), and they highlight the following advantages of their click technology:

- Tool-free assembly: needs only two hands and a small punch
- Easy and fast: assembly of furniture units in a few simple steps directly on the construction site
- No permanent connection: quick dismantling if necessary
- No visible and visually disturbing connections

Fig. 35.50 A furniture particleboard click system from the EGGER company. (Photo D. Sandberg)

- A strong click connection, with form-fitting tongue-and-groove
- An optimized process: delivery directly to the construction site

35.5 Complex and Efficient Geometries in Timber Construction

The growing timber-manufacturing industry faces challenges due to the increasing geometric complexity of architectural designs. Complex and structurally efficient curved geometries require intensive manufacturing and excessive machining, which are aided by a combination of digital design and computer-numerical control (CNC). The construction engineers know how to make use of digital tools, with geometric imagination capabilities and construction know-how, while the architects have ambitious ideas for creating extraordinary buildings.

Digital design and production using computer-aided engineering (CAE), computer-aided design (CAD), and computer-aided manufacturing (CAM) have allowed timber construction to forge ahead into new fields. Innovative connections, modern wood-based materials, and cutting-edge CNC milling offer entirely new possibilities, and wood can be shaped into almost any conceivable form. Nowadays, flexible planning-design tools and CNC processes allow us to design and build extraordinary architectural structures (Fig. 35.51). Stages in the construction process are now available, from technical development to construction, service, and maintenance.

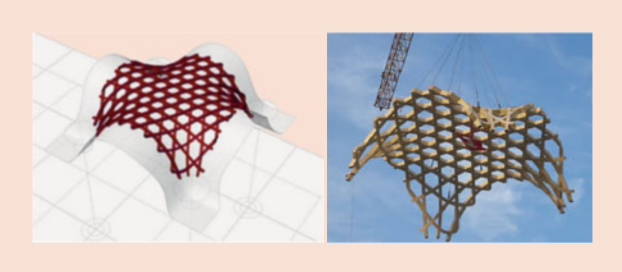


Fig. 35.51 Digital simulation of the construction and part of a roof during assembly. The Haesley Nine Bridges golf clubhouse in Yeoju, Republic of Korea. (Shigeru Ban Architects, photo Blumer–Lehmann AG, Switzerland)

The framework for producing components is full of mathematically exact, parameterized models of the structure and its components, and this ensures that tolerances are kept to a minimum in the construction, processing, and installation phases. Together with high-quality code-free and error-free information for CNC machines, 3D modeling is also critical for prototyping parts and for the management of 3D printing. These models are part of the entire process from project development, feasibility studies, and design, over the CAD/CAM processes, to the construction itself.

Depending on the type and complexity of the structure, specialists in CAD and CAM software can convert graphic data into machine codes and steer 5-axis CNC processing. The coordination of the various stages, architectural design, structural engineering, production, logistics, site facilities, installation, and follow-up work is a core element of contemporary project management, and production companies are becoming IT specialists, providing services and solving interfaces, while carpenters coordinate the building processes. There are intelligent machines, but the digital process (CAD-interface CAE and CAM) still needs a lot of detailed planning (Fig. 35.52).

Modern design and production methods open up many possibilities where complex structures and buildings become real. Free-form structures are distinguished by their cellular supporting structures and the unique nature of each component. They are exceptional – from the initial idea through to the design, production, and installation with the required quality, in the specified time frame – and cost-effective from the perspective of the investor and builders.

Fig. 35.52 Digital planning process CAD-CAE-CAM interfaces in the construction of the Swatch headquarters, Swatch and Omega campus in Biel, Switzerland. New dimensions in complexity in timber construction. (Shigeru Ban Architects, photo Blumer-Lehmann AG, Switzerland)

In contemporary architecture, the timber structure remains visible as a dominant factor of the architectural expression, and it is often based on principles of nature.

Creating exceptional free-form structures requires an intensive and close cooperation between specialists. Developing the geometry, designing the supporting framework, and generating production data are all decentralized, yet interconnected, processes. An integrated exchange of data with clearly defined interfaces makes seamless project management possible.

Advanced prefabricated timber structures save money at the construction site because they allow exact planning and rapid assembly as a result of prefabrication. This is also an economic benefit for builders when the time between new construction and rental is short. For investors, it is important that advanced financing and the marketing of the property take less time and that on-time completion is assured. One of the main advantages of the modern in-factory rather than on-site production concept for timber structures is that the construction method is primarily dry, so that there is less risk of damage to the structure as a result of moisture [252].

In the following section, three different systems are described to achieve a construction with a very complex shape, or to achieve efficient material utilization by element geometry:

- Construction with straight solid-wood components
- Construction with bilayer elements
- Construction with tubes

35.5.1 Construction with Flat Solid-Wood Components

Sawn timber is a simple and inexpensive building material. Sawn timber is sufficient as a material and requires only elementary fasteners for joining and primitive support or hoists for assembly. No other type of construction achieves such an effect with such meager resources. Nevertheless, the use of wood is in most cases wasteful, and great efforts are required to use this resource so that it makes the greatest possible contribution to sustainable development. Only if building with wood succeeds in moving out of its niche will the forest and timber industry be heard in the discussion of sustainability.

Frei Paul Otto (1925–2015), German architect active in the early part of the twentieth century, was noted for his use of light-weight structures, with a prevalence of tension forces in the roofing system and by limiting of compression forces to a few support members. An example is the domed shell structure of the auditorium of the German Pavilion at the World Exposition in Montreal in 1967, produced by deformation of a plane lattice grid of hemlock wood [253]. In 1974, the multifunctional hall in Mannheim, Germany, designed by Frei Otto, Carlfried Mutschler, and Joachim Langner, was completed. With a roof area of 9500 m^2, and spans of upto 61 m, this lattice-roof structure was an early example of a self-supporting timber grid shell structure, and the work by Frei inspired other architects and timber engineers to construct shell structures in timber.

In 1991, a timber shell construction was built on the campus of the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, under the leadership of Professor Julius Natterer – a pioneer in complex and efficient geometries in timber construction. This was a spherical stacked board dome with a square floor initially laid out with a network of intersecting board lamellae. The construction site equipment was limited to four sets of scaffolding with pulleys, with the help of which the dome was gradually raised so that it could be joined at the nodes with screw bolts. In this way, a filigree-supporting structure was assembled with the help of simple hoists and pulleys. The outer board formwork was used for stiffening.

Fig. 35.53 Roof for the world exhibition “Expo 2000” in Hannover, Germany

Simply curved structures such as barrels are also suitable, where the orientation of the boards corresponds to the flow of forces in the supporting structure. The Morges shipyard was the first of its kind. If the barrel is brought together to form a ring, a torus is formed which, at the St. Quentin swimming pool, was stiffened with a stacked board ceiling. The highlight so far in Julius Natterer’s work is the roof for the world exhibition “Expo 2000” in Hanover shown in Fig. 35.53.

This technique is still not in common use, but there are companies that have this construction technique as a speciality, including the Swiss Blumer-Lehman company (Fig. 35.54) and the German HESS Timber company.

35.5.2 Bilayer Construction

The production of curved and layered wood-based panel structures has followed biological role models such as the bending of pine cone scales (cf. Sect. 35.2), and the biomimetic concept of bilayered laminated wood has been introduced by Wood et al. [254]. They have developed an efficient form-giving mechanism for large-scale curved solid wood panels using bilayered structures capable of self-shaping as a result of changes in moisture content. The controlled warping of layered wood-based panels is still a challenging task in the development of thin engineered wood products. As an anisotropic and hydrophilic material, wood tends to change its volume and mechanical properties with changing moisture content, and the mechanical properties of certain adhesives are also sensitive to moisture changes. A moisture change in the adhered wood leads to different stress and strain states between the wood layers, and adhesives with different moisture-related properties participate differently in this interaction. The challenge also lies in the requirement of profound material knowledge for analysis and prediction of the deformation in function of setup and boundary conditions. Using time- and moisture-dependent mechanical simulations, the contributions of different wood-specific deformation mechanisms on the self-shaping of large-scale elements can be demonstrated (Fig. 35.55).

Fig. 35.54 A free-form timber structure. The Haesley Nine Bridges golf clubhouse in Yeoju, Republic of Korea. (Shigeru Ban Architects, Photo: Blumer-Lehmann AG, Switzerland)

The bilayer approach is described in Sect. 35.2 and is here mentioned as a special application developed by Grönqvist et al. [255].

The Urbach Tower shown in Fig. 35.56 is a unique wood structure based on a self-shaping process of curved wood components, a paradigm shift in timber manufacturing from elaborate and energy-intensive mechanical forming processes requiring heavy machinery to a process where the material shapes itself, driven by the characteristic shrinking of the wood when the moisture content decreases. This opens up new and unexpected architectural possibilities for high performance and elegant structures. The Urbach Tower was the first structure in the world to be made from self-shaped, building-scale components, providing a striking landmark building for the City of Urbach’s contribution to the Remstal Gartenschau 2019.

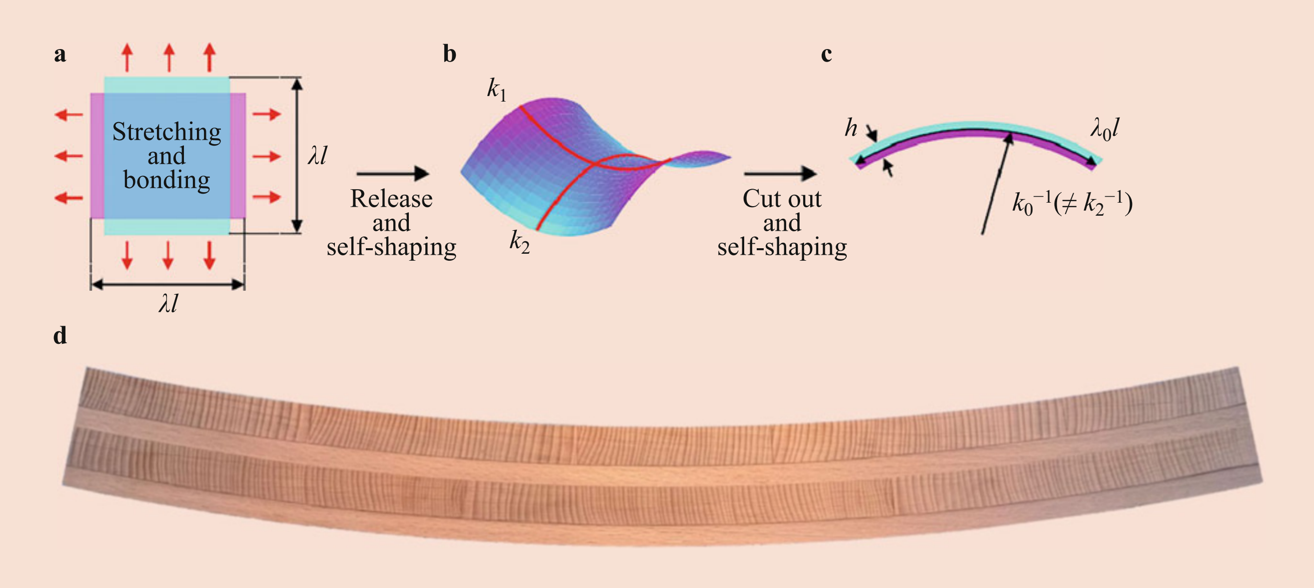


Fig. 35.55 The curvature of a bilayer-composite: (**a**) Two elastic sheets of thickness h/2 are stretched by a factor λ and then bonded together. The same configuration can be achieved by first bonding two stimuli-responsive layers together and inducing λ with the stimuli, e.g., a moisture-content change in wood will result in anisotropic swelling or shrinkage-induced stretching in the single layers, (**b**) upon release, the bilayer-composite plate-like sheet self-shapes into a saddle configuration with principal curvatures k_1 and k_2; (**c**) a narrow quasi-2D strip cut from the sheet displays natural curvature k_0 and stretch λ_0 [254], and (**d**) cross-section view of a four-ply bilayer-composite of European beech. (Photo D. Sandberg)

Fig. 35.56 Timber tower made of 14 m-long elements shaped by a self-shaping process to achieve curved timber elements (The Urbach tower in Urbach, Germany). (Photo ICD_ITKE, University of Stuttgart)

The development of large-scale self-shaping is a paradigm shift in timber manufacturing to a process where the material shapes itself. The bilayer parts are manufactured with a high wood moisture content and dried in a standard technical drying process. When they are removed from the drying chamber, the parts are precisely curved, overlapped, and laminated together to lock the geometry in place, forming large curved laminated components with a shape-stable geometry. The technology of self-shaping manufacturing for solid timber panels and the rapid adaptability of the process to different curvatures open up new architectural possibilities for thin shell wood structures, using a sustainable, renewable, and locally sourced building material.

Key features of curved and layered wood-based panel structures are the transfer of biological role models into structural planning and design of timber constructions, and modeling timber structures based on precise wood material data.

35.5.3 Tube Elements

Cylindrical LVL

Cylindrical EWPs was developed in the in the first half of the 20th century and has since then been used in different specialized application [Kollmann]. The manufacture of cylindrical laminated veneer lumber (LVL) was developed, at the Wood Research Institute, Kyoto University, in 1994 [256], based on the of manufacture of paper tubes by winding sheets around a cylinder reproducing the natural winding of the microfibrils on a macroscopic level. The raw material for the cylindrical LVL is veneer tapes, as shown in Fig. 35.57.

Fine strips are cut from a veneer with a thickness of 1–4 mm with plastic thread to hold them together as flexible veneer tapes. The width of these tapes depends on the diameter of the cylinder and the mechanical performance required. The various stages of winding the veneer tapes on a mandrel to manufacture the cylindrical LVL are shown in Fig. 35.58.

The veneer tapes are wound in a spiral of several layers around a mandrel to form the cylindrical LVL. The first layer is wound in a spiral without adhesive, whereas the subsequent layers contain adhesive, and the direction of winding is alternated from one layer to another. This gives the wall of the LVL an orthotropic behavior. Figure 35.58 shows the winding of the veneer tapes.

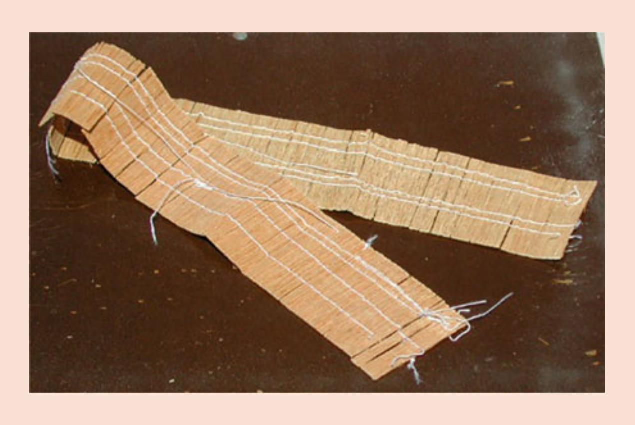


Fig. 35.57 Veneer tapes used in the manufacture of cylindrical LVL

A resorcinol or isocyanate adhesive is spread on the back of the veneer tapes in an amount of approximately 25 g/m^2. At the end of the process, a rubber belt is wound to apply a pressure of approximately 0.4 MPa on the LVL cylinder, and the adhesive is cured by an oil circuit inside the sleeve heating the LVL. After the adhesive has been cured, the sleeve is withdrawn from the LVL (Fig. 35.59).

The cylindrical LVL can be used in various ways, e.g., as a structural element in building construction, as a pipe for the transport of fluid, or as a guide for electrical wiring. This type of composite cylinder is being used to an increasing extent in the construction industry. It is possible to manufacture hollow columns having a length of 12 m and a diameter of 1.2 m with various layer orientations, giving it excellent mechanical properties and making it very suitable for use as a construction material.

The Haller System

Professor Haller at the Dresden University of Technology [259, 260] suggested that load-bearing profile cross sections could be produced by an open thermo-hygro-mechanical process (Fig. 35.60). Compared to metals and plastics, the

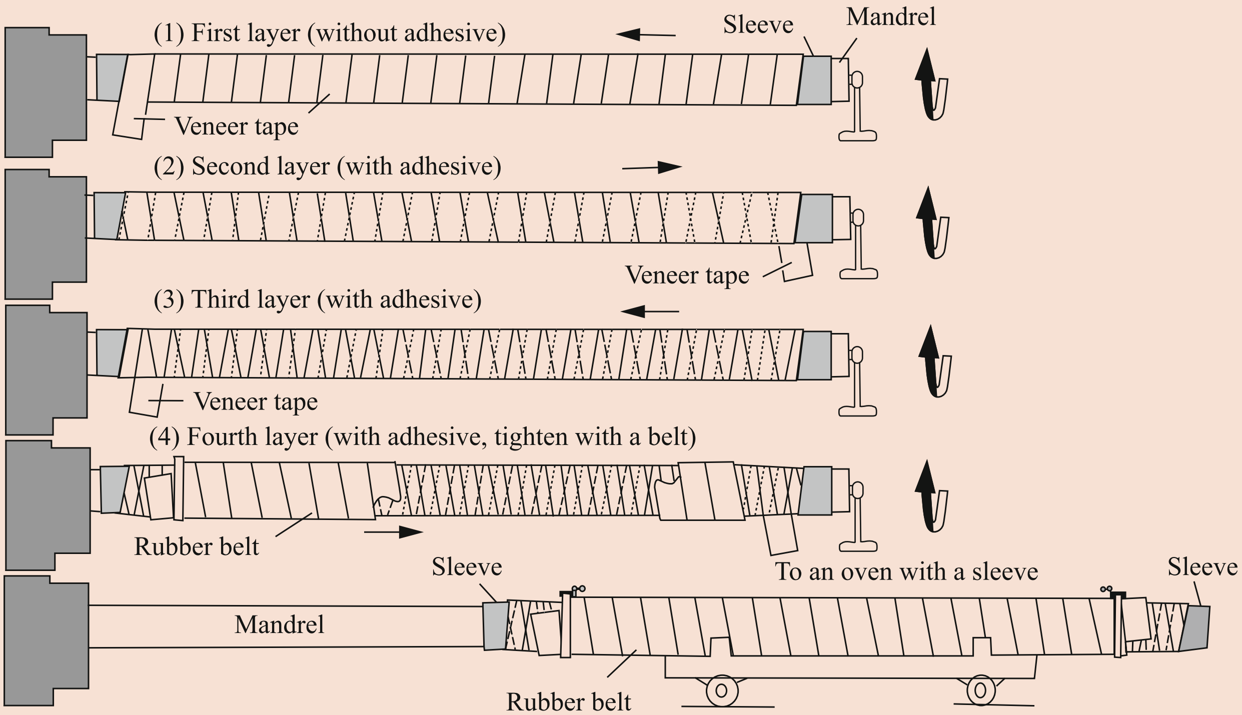


Fig. 35.58 Winding of the “veneer tapes” to produce cylindrical LVL [256–258]

Fig. 35.59 Segments of cylindrical LVL

maximum tensile strain that sawn timber can withstand is low, and this prevents shaping, but Haller [261] emphasized that a high load-bearing capacity can be achieved if an EWP is used instead of sawn timber.

In the manufacture of tubes [261, 262, 266], spruce boards with an initial moisture content of 12% were densified at 120 °C and cooled to 80 °C to create edge-glued panels. The panels were then pretreated in a steam chamber before being formed into tubes, as shown in Fig. 35.61. This technology allows tubes to be produced with any longitudinal and transverse dimensions, the radius depending on the degree of densification.

A fiber reinforcement of glass or carbon and epoxy resin on the outer surface of the tubes considerably increases the load-bearing capacity, the ductility, and the durability of the wooden tubes [263]. Molded wooden tubes can be produced by panels of beech wood densified to about one half of the initial volume transverse to the fiber direction. The resulting hollow sections have a higher load-bearing capacity than solid sections with the same material volume. These molded wood tubes are however being produced only on a pilot state.

Key features of wood-based tubes are circular cross-section suited for columns, high mechanical strength due to densification of the wood and fiber reinforcement, and piping material for chemically aggressive liquids (e.g., brine).

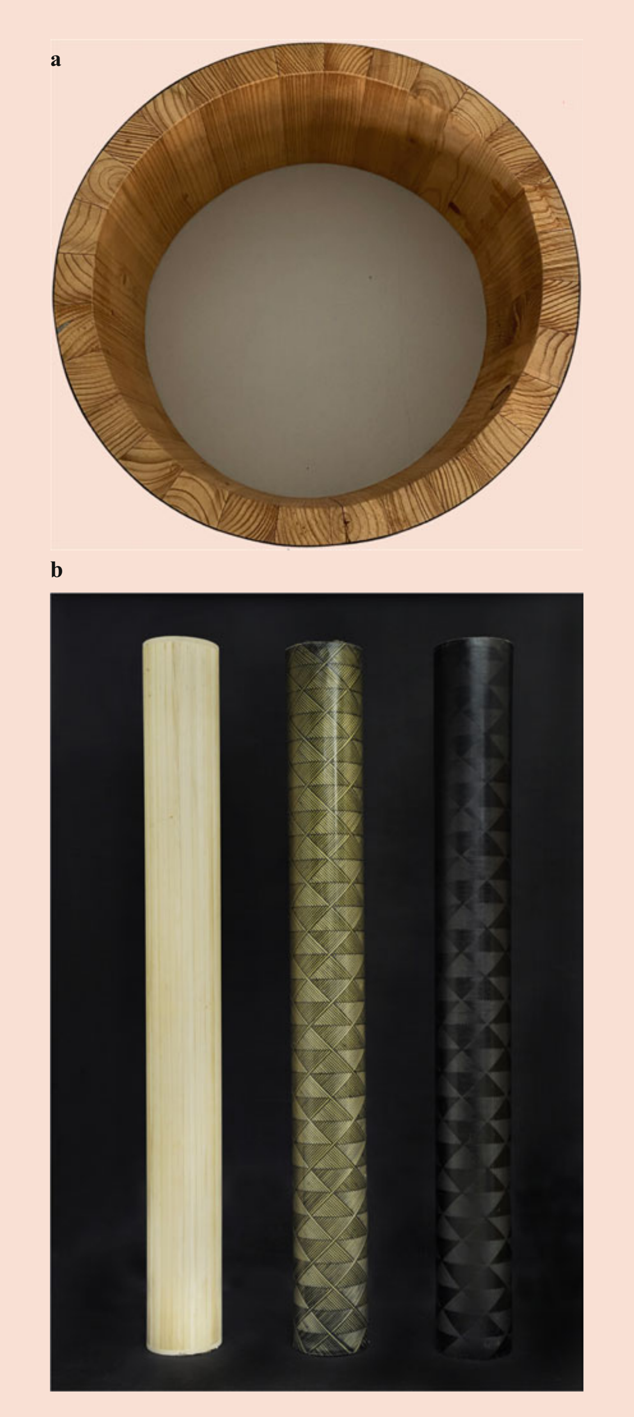


Fig. 35.60 Molded wooden tubes: (**a**) cross-section view, and (**b**) tubes without and with fiber reinforcement, tube length ca. 4 m. (Photo Dick Sandberg and L. Sprenger)

Wind-Turbine-Tower System

Wind turbines place very high demands on the materials used, the stresses being high and dynamic, compounded by ever increasing dimensions and weights. More steel is being used in the wind-energy industry than in shipbuilding, but steel is more expensive than wood, and the production of steel is more carbon intensive. Towers up to 200 m high can be constructed, and several attempts to make the wind-turbine tower in wood have been presented, one example being the Haller system for molded timber tubes (cf. Fig. 35.61). Two companies have based their production

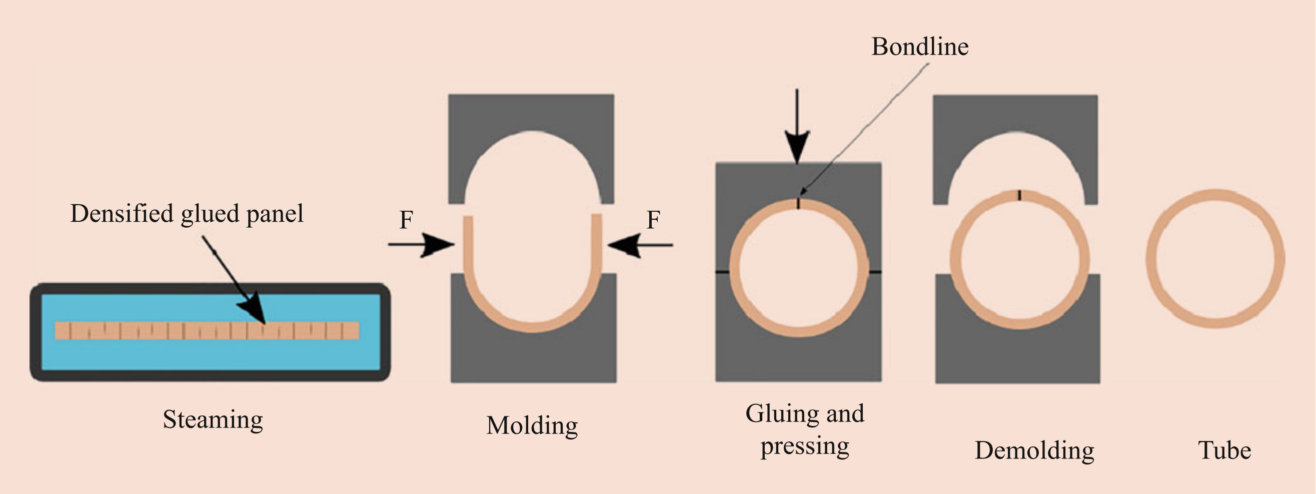


Fig. 35.61 Schematic manufacture of a wooden tube. F - transversal load for forming

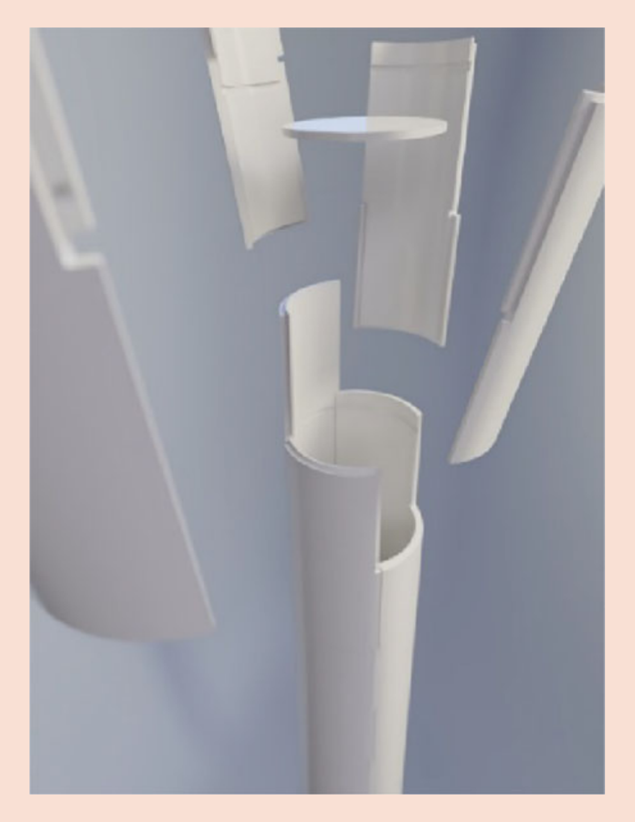


Fig. 35.62 The Modvion wooden wind-tower system

on cross-laminated timber or glued-laminated timber of Norway spruce, the towers being assembled on-site into a closed, hollow body.

In 2012, the German company Timber Tower put the first cross-laminated timber (CLT) wind turbine into operation in Hannover, Germany [264, 265]. This wooden tower is 100 m high and operates a 1.5 megawatt wind turbine that produces electricity for about 1000 households. The outer tube construction is made of Norway spruce cross-laminated timber. In a tower with a height of 100 m, the lowest segment has a base area of approximately 7 × 7 m and the top is 3 × 3 m. This structure should be able to withstand very high dynamic stresses at heights of up to 200 m, as well as the weight of the rotating nacelle and rotors. A single rotor blade can weigh 8–9 tons, and those being developed may be even larger and heavier. 320 m^3 of timber was included in the Hannover tower construction.

Modvion is a Swedish company developing modular designs in renewable engineered wood products, and their current area of focus is in wind-tower technology. Modvion's patented module technology enables significantly decreased cost, efficient transportation, and streamlined installation of towers exceeding 120 m (Fig. 35.62). Ultimately, this results in increased cost efficiency in the harvesting of wind resources.

As wind towers rise above 100 m, transportation poses considerable problems given that base diameters exceed 4.3 m, which is the limit for transport width in most of the USA and in the EU.

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