

Review Articles

Use of Forest Resources as Woody Material with Structural Elements Ranging from Lamina to Nanofiber

SUZUKI Shigehiko (President, Shizuoka Professional University of Agriculture)

Summary:

The status of forest resources in Japan was reviewed for forest stock volumes, carbon storage, biomass, and harvested wood products. This paper summarises the historical background and development of wood products, including technology and structural element dimensions, and presents research by the author on the structural element characteristics of lamina, veneer, strands, particles, fibers, fines, and nanofibers.

Keywords: forest resources, HWP, wood-based material, element size, lamina, nano-fiber

1. Forest resources in Japan

This report summarises topics on forest and wood science from a resource and environmental use perspective. Figure 1 presents the potential and growth of forest resources in Japan. From the late 1940s, intensive development of domestic conifer plantations markedly increased total forest resources, whereas natural forest resources remained unvarying. In 2017, natural forest and plantation resources comprised of about 1.9 and 3.3 billion m³, respectively^[1].

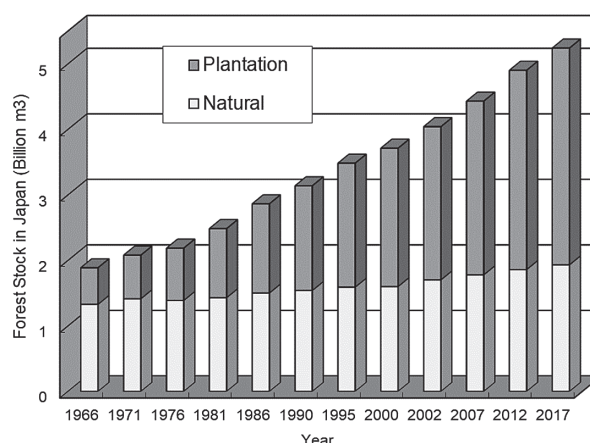


Fig. 1 Change of growing stock of forest in Japan

Use of plantation species has been an important issue not only for forest policy but also for the overall Japanese wood industry. The Japanese cedar or sugi (*Cryptomeria japonica* D. Don) has the largest planted area, and the Japanese cypress or honoki (*Chamaecyparis obtusa* Endl.) has the second largest, followed by larch (*Larix* spp.), pine (*Pinus* spp.), and others^[2]. Sugi is a fast-growing species and the most common plantation species, covering 44% of the total planted area. The mechanical quality of sugi is comparable or slightly lower than imported species, such as Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) from North America, and spruce (*Picea* spp.) from Nordic countries. Furthermore, processing problems arise due to high moisture content and the difference between sapwood and heartwood. However, sugi usage in the construction sector has recently increased with technological developments in wood drying, lamination, and rotary lathing.

2. Perspectives on forest biomass in Japan

Forest stock volume refers to the total trunk volume of a forest that can be utilised as woody material. Forest biomass abundance includes the volume of branches, leaves, and roots. Thus, the

biomass quantity can be calculated as 5.24 billion m³ (forest stock) \times 1.6 (expansion factor incorporating additional volume other than the trunk) \times 0.45 t/m³ (volume density) = 3.77 billion t^[3]. Here, the expansion factor of 1.6 was employed from various estimates; in the Intergovernmental Panel on Climate Change (IPCC) report, this factor was defined more precisely as $BEF \times (1 + R)$, where BEF is a biomass expansion factor in the narrow sense and R is the root-to-shoot ratio^[4]. The carbon storage of Japanese forests is estimated as 3.77 billion t \times 0.5 (carbon fraction of dry matter) = 1.89 billion C t. This value can be converted into a carbon dioxide estimate by multiplying by 44/12. Thus, Japanese forests absorb an estimated 6.92 billion tonnes of carbon dioxide. In comparison, Japan's total fossil energy supply per year, as carbon dioxide, is 1.2 billion t^[5].

Apart from forests' contribution to the global carbon cycle, the Fifth Assessment Report of the IPCC notes that woody materials (harvested wood products, HWPs) mitigate climate change through three effects: a carbon storage effect, a material substitution effect, and an energy substitution effect^[6]. The direct use of HWPs is carbon storage, as wood is 50% carbon by weight. Second, the substitution of other materials with HWPs reduces fossil fuel consumption and energy use. Third, HWPs can be used as fuel after their long-term use as stored carbon.

Among HWPs, woody materials used in construction, housing, and furniture are called wood-based materials. Those re-constituted wooden materials are categorised into two groups: timber products with a beam or pole shape, and panel products with a flat shape (e.g. plywood).

3. Transition of the structural element dimensions of woody materials

This section discusses the history of HWPs from a structural and technology perspective. Figure 2 illustrates the transition of the element size of wood-based materials such as timber products and panel products. After a long history of using solid timber for construction, glued laminated timber (GLT) was invented in the 1890s^[7]. The volume of lamina, based on typical dimensions such as 25 mm in thickness, 200 mm in width, and 2000 mm in length, is in the order of 10 million mm³. Using this as a starting point, we can track the progression of timber product development.

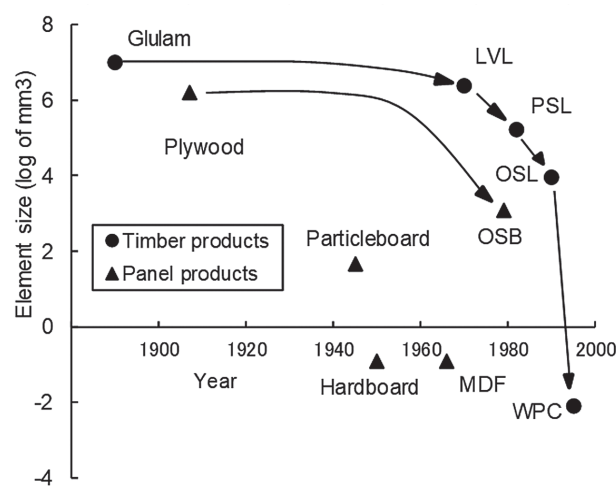


Fig. 2 Transition of the element dimension of woody materials

Laminated veneer lumber (LVL) consists of veneer with a typical volume of 5 million mm³, and the veneer strand for parallel strand lumber is approximately 100,000 mm³. Oriented strand lumber (OSL) is also a timber product with wood strands, with a volume of 10,000 mm³, and a thickness of 1 mm, a width of 30 mm, and a length of 300 mm. Lamination technology is critical in GLT production, veneer lathing is the breakthrough innovation for both LVL and plywood, and stranding technology for OSL enables effective use of forest resources, especially for less used or low-quality wood species.

The element size of wood-plastic composites (WPCs) is plotted in Figure 2. Assuming that wood powder is a cube of about 0.2 mm per side, its volume is about 10^{-2} mm^3 . It is challenging to define WPC as a timber product, as no grain orientation is made in this material. However, some WPC products are used as timber products for outdoor decking or fencing^{[8][9]}. Defining WPC as a timber product would substantially impact the history of wood-based materials. The element size of timber products started at 10^7 mm^3 in GLT, declining to 10^3 mm^3 in OSL, and drops sharply to 10^{-2} mm^3 in WPC. Thus, wood element dimensions have been decreasing logarithmically based on the development of processing technology.

Advances in technology have made it possible to use smaller structural elements, which has broadened raw material selectivity and expanded the potential use of forest resources, from large- to small-diameter logs and less used or low-quality logs.

4. Lamina to nanofibers

Over a period of about 40 years, the author has been involved in the material use of forest resources. Table 1 shows a list of representative research topics from the perspective of structural elements. Lamina is the largest element used in GLT and cross-laminated timber, and element size decreases to the nano-scale for cellulose nanofiber (CNF) reinforced composites. The rationale for this development is explained through the introduction of several research projects.

Table 1 Elements and research topics on wood-based material

Element	Research topic
Lamina	GLT, durability, CLT
Veneer	sugi plywood
Strand	orientation, J-OSB
Particle	raw material, consolidation
Fiber	defibration, nail resistance
Fines	WPC, powder board
Nano	fibrilated surface, binding

4.1 Lamina used for GLT construction

Wood resources are most frequently used in the building sector and the paper industry. Figure 3 presents the GLT supply and use in large timber construction in Japan. Recent data show that 1.5 million m^3 of GLT is produced domestically, and 0.8 million m^3 is imported from overseas.

However, GLT does not have a long history. A Japanese Agricultural Standard for Structural GLT with Large Dimension was established in 1986^[10], and the Building Code was revised in 1987 for three-storey wooden houses. After that, large timber construction was approved, and GLT supply increased markedly. Moreover, about 400 GLT buildings were built in 1995, and 200 are currently constructed every year (Figure 3). With news reports of GLT being used in the main stadium for the Tokyo Olympic Games, the value of wooden construction is being recognised again.

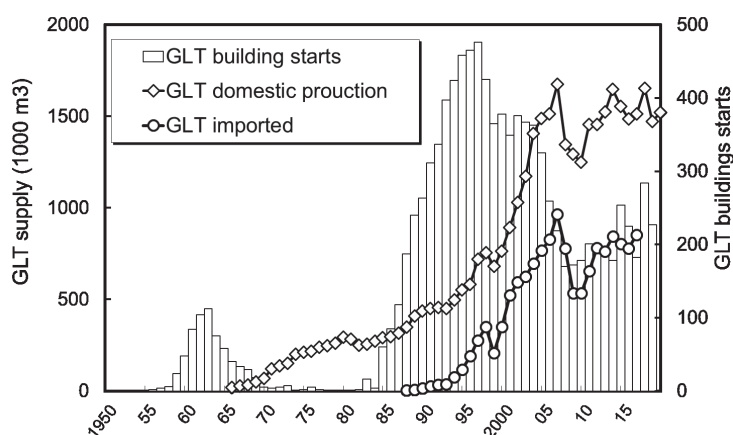


Fig. 3 GLT supply and GLT building starts in Japan

Within this research field, durability is a critical topic. Resorcinol formaldehyde resin (RF) and phenol FR have been used widely in structural GLT, and durability has been demonstrated. Aqueous polymer-isocyanate adhesive (API) was later approved as an adhesive and used for residential housing. However, there is insufficient scientific proof of the durability of API. Therefore, a research project was initiated to confirm the durability performance of API. The lab-scale experiments using small specimens were insufficient. Therefore, a commercial mill joined the project to produce a prototype of GLT bonded with PF and API for practical applications. Several accelerated ageing tests proved that API-bonded GLT had durability equal to or higher than RF ^[11].

4.2 Veneer used for plywood

Veneer is well known as a part of plywood, and we initiated a research project on this panel product. Around 2000, while the momentum for using domestic conifer (sugi) for plywood was rising, Siberian larch was used as a reinforcing material. Since the use of old-growth wood from Siberia was considered environmentally unfavourable, we chose *Eucalyptus grandis* W. Hill ex Maiden, a plantation species used in the mining and construction fields, to investigate its effects on plywood properties when combined with sugi (Figure 4). Arranging eucalyptus veneers on the surface of the panel yielded stiff, strong plywood because the elastic modulus of eucalyptus is about twice that of sugi; plywood with eucalyptus veneer on the surface had an elastic modulus of 6.13 GPa, while that of sugi veneer plywood was 3.85 GPa ^{[12] [13]}. The plywood samples were further tested for use in construction and processing into furniture. Third-party evaluations of these plywoods produced an unexpected result. Many people highly valued the plywood with sugi veneer on the surfaces, even though it provided reduced strength. During the rotary lathing process, less than 10% of sugi veneers had excellent quality that could be used for facing. Through this project, it was found that Japanese people loved the appearance of sugi and preferred to use domestic conifers for housing and furniture.



Fig. 4 Imported *Eucalyptus grandis* logs before being processed into veneer

4.3 Strands for oriented strand board (OSB)

In the late 1980s, OSB or medium-density fiberboard (MDF) was highly marketed in the forest sector. OSB successfully became the substitute for softwood plywood in North America ^[14], while MDF became the alternative to particleboard in Asia to meet the increasing demand for wood-based panels. Some Canadian panel producers had realised a significant market potential for OSB in Japan ^[15]. A drastic decline occurred in Southeast Asian timber supplies, while the number of the housing starts remained the same.

The advent of OSB was exciting for the wood panel world. Its commercial production began in 1982 and has grown exponentially as an alternative to structural plywood. Figure 5 shows the distribution of OSB mills in 1995. In just 15 years, production volumes expanded, and the raw

material shifted from aspen in the north to southern pine in the south. The conversion from plywood to OSB meant a major conversion of the structural elements from veneers to strands. Moreover, the raw material for structural panels changed significantly from large-diameter softwood to small-diameter and unused forest species.

Under these conditions, OSB production in Japan was explored. One of the solutions was a type of panel made with sugi strands for surface layers and demolition wood particles as the core layer (Figure 6), called J-OSB^{[16] [17]}. At that time, the use of sugi thinnings was a major issue in forestry. With growing environmental awareness, the use of recycled wood from building demolition also became a political problem.

4.4 Particles for particleboard

The configuration of particles as the major component of wood product structure has garnered substantial interest since the first study on this topic by Turner in 1954^[18]. Much research has been conducted on element shape, wood species, board density, layer structure, and adhesive type for practical applications. Pressing conditions are also important variables for board consolidation.

Despite continued efforts, the process that occurs during pressing has not been clarified. To address this, computer simulations have become popular^{[19] [20]} to advance our understanding; however, measurements are superior^{[21] [22]}. Figure 7 presents temperature and vapour pressure measurements within a particleboard mat during hot pressing^{[23] [24]}; the plateau temperature changed with board density, and board density also strongly affected the vapour pressure behaviour. Heat and mass transfer factors during



Fig. 5 Distribution of OSB mills in North America at 1995 (■: existing, and □: planning)

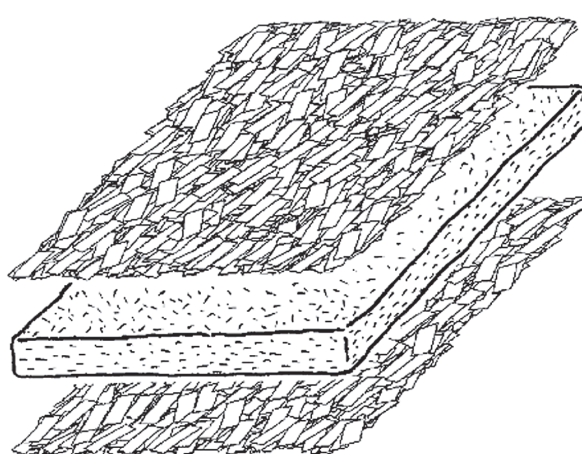


Fig. 6 The structure of J-OSB (faces: sugi-strand, and core: demolition wood particle)

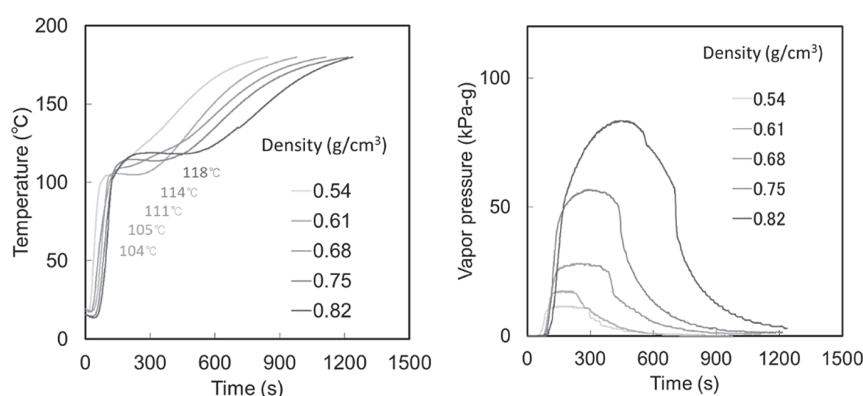


Fig. 7 Temperature (left) and vapor pressure (right) behavior inside the particle mat during hot pressing.

pressing have a significant influence on the panel's physical and mechanical properties, and further investigations will be continued to achieve effective use of forest resources.

4.5 Fibers for MDF

Experimental studies on panel manufacturing, using fiber or fiber bundles as elements, are difficult at the laboratory level because automation in MDF manufacturing is highly advanced, for example, resin blending in the blow line after the defibration. In small-scale trials, we could fabricate a uniform MDF mat by re-unravelling the mechanically blended fibers. In this way, some studies on wax addition to improve water resistance, and the clearance of the defibrator discs, have been experimentally verified.

Strands, particles, and fibers described here may be collectively referred to as particle types, which are united by a common manufacturing principle. The physical behaviour of these panels during hot pressing is summarised in Figure 8, which simplifies the complex behaviour described by Maloney ^[25] and Bolton ^[19]. Here, the mat formed with furnish after blending with resin is composed of 14 parts moisture, 8 parts thermosetting resin, and 100 parts wood when this mat is compressed at 200° C and 3 MPa. First, the water in the surface layer becomes steam and starts moving inside, as shown by the sudden temperature rise in Figure 7 (left). The first stage of temperature increase is due to water vapour movement (convection), and the second stage is due to heat transfer (conduction) ^{[19] [22]}.

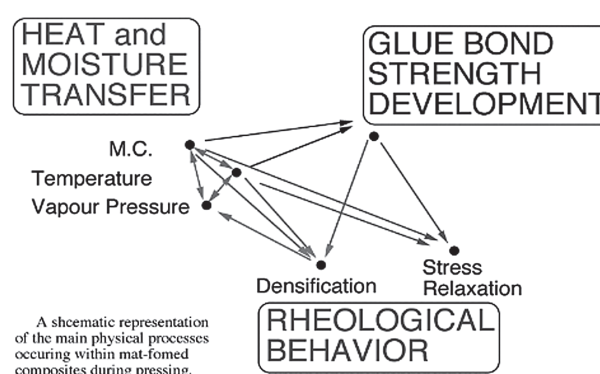


Fig. 8 Physical behavior of the mat during hot pressing

As shown in Figure 8, moisture, temperature, and vapour pressure change in a physically balanced manner, and the increase in temperature promotes resin curing. Meanwhile, the wood furnish may be consolidated under the effect of temperature and moisture. Concurrently, the reaction force against compression is released. Resin curing contributes to the physical properties of the mat. Research efforts are underway to elucidate this series of processes.

4.6 Fines / Powders

The use of wood powder was of great interest because it was thought that reducing the element size would improve the selectivity and yield of raw materials, promoting its effective use. Wood powder board can be easily produced by hot pressing the mixture of wood powder and thermosetting powder resin ^[26]. However, this material is not commercially widespread. The most famous product using wood powder is wood plastic composite (WPC), which is material made of wood powder/wood flour and thermoplastic such as polyethylene, polypropylene, or polyvinyl chloride. The author started WPC research in collaboration with Dr. Wu (Louisiana State University) ^[27] in 2006.

Understandably, the surface texture of wood powder affects the material's performance, but WPC is different from the above-mentioned mat-formed panels. Since wood powder (filler in this case) is

hydrophilic, and plastic is hydrophobic, research has mainly concerned the compatibiliser that connects the wood and plastic. From 2011 to 2013, the author conducted the project titled “Demonstration research of a consistent system from thinning to functional WPC conversion at the forestry site” supported by an MAFF Research Subsidy of Practical Technology Development Project ^[28]. The second motivation for this research project was to confirm the fibrillated surface’s mechanical effect ^[29], the first effective use of forest resources.

4.7 Nanofibers

Woody material research shifted focus on the nano-scale fibrillated surface phenomenon, where the binder effect for the composite would be expected ^[30]. It matched the direction of the element size reduction. At that time, great progress in CNF research was made by mechanical pulverisation ^[31] and chemical (TEMPO) ^[32] methods.

CNF research involvement of the author can be summarised in the following three points. (i) In 2015, Dr Isogai was awarded the Marcus Wallenberg Prize, and the author was invited to the ceremony and seminar in Stockholm ^[33]; thus, CNF research has been highly valued. (ii) CNF was also noted in the Japan Revitalization Strategy / Revision 2014, 2015, and 2016 ^[34]. As such, it has also attracted attention as an administrative issue. (iii) In June 2015, Shizuoka Prefecture launched the “Fujinokuni CNF Forum” with the participation of companies and related organisations for collaboration ^[35].

The author also participated in a project to improve housing insulation using CNF as additives supported by the Ministry of Environment Commissioned Work [36]. Improving insulation contributes to carbon emission reductions. CNF-containing housing components for exterior wall, ceiling, and flooring materials were mass-produced, and their performance evaluated. Optimal material formulation, blending conditions, production facilities, and economic viability were determined ^[36].

The experimental results of CNF addition to wet-process fiberboard showed that both the modulus of elasticity (MOE) and modulus of rupture (MOR) increased as the addition rate increased. As shown in Photo. 1, aggregated CNF was attached to the surface of the wood fiber. The formation of agglomerates is a problem for the use of CNF as additives; however, the cohesive force due to hydrogen bonds enhances the mechanical properties of the fiberboard.

There are various debates and proposals regarding CNF research. Statements have been made such as “The boom in CNF research has reached its peak, or is disappearing”, “The research seemed to have been driven by the government”, “The time is approaching when academic evaluation is required”, etc. Regardless, there is no doubt that CNF is a natural

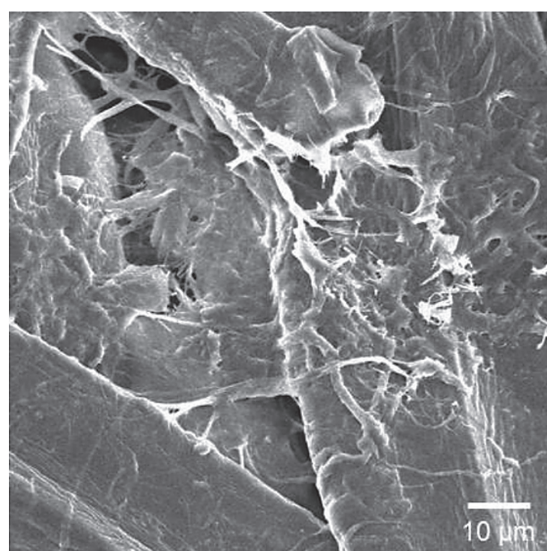


Photo. 1 CNF agglomerates attached to wood fibers

organic material with potential. If CNF could be used as a timber product, the structural element could decrease from 10^7 mm^3 to below 10^{-10} mm^3 ; the history of woody material development moves on a logarithmic scale.

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