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Update on Research on Transparent Wood

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Update on Research on Transparent Wood

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Abstract. This article focuses on various methods of creation of transparent wood, which are derived of the original invention of transparent wood fabrication and describes the advantages of each method, newly obtained properties of the composite materials and suggestions of its possible use in building industry and architecture.

1. Introduction

Transparent wood – an invention first introduced by Siegfried Fink in 1992, who turned wood transparent to be able to observe its specific structures [1]. His work was rediscovered between years 2015 and 2016 by teams at Swedish KTH Royal Institute of Technology [2] and at University of Maryland [3]. Both teams were inspired by Fink's process of fabrication of transparent wood, which they modified to suit their needs and unlike Fink, they were examining properties of transparent wood itself. Both the processes were different, but the concept of creation of transparent wood was the same. The first step was to delignify the wood sample, as lignin gives wood its colour (at KTH, they used 1 wt% $NaClO_2$ with acetate buffer solution with pH 4.6 at 80°C; at Maryland, they used boiling solution, which contained NaOH and Na_2SO_3 and then, the samples were transferred into a solution of H_2O_2 to remove the remaining lignin). Delignified wood samples were then white. After, the second step was undertaken, which was to fill the sample with transparent polymers having matching refractive indexes under repeated vacuum and de-vacuum (PMMA at KTH and epoxy resin at Maryland). After the second step, transparent wood sample was obtained. Both teams then researched properties of their transparent wood samples and found that the thicker the sample was, the lower was its optical transmittance (the highest value of optical transmittance of 90% was measured for the 0.7mm thick TW sample, while for the sample of 3.7mm thickness, its optical transmittance dropped significantly at about 40%). Another finding was that transparent wood has high values of optical haze between 90% and 100%. The very important discovery, considering use of transparent wood in building industry, were its mechanical properties that were improved compared to both, the original wood and the original polymer. Researches then suggested its possible applications for lightweight low-cost structures in light-transmitting buildings, transparent solar cell windows, furniture, or as structural material in automobiles and optoelectronics. They were claiming the better cost and improved ecology compared to glass. However, there was some criticism about those claims, mainly caused by use of chemicals needed to delignify the wood and because of limited thickness, which can still become transparent and be fabricated. Having this criticism in mind, scientists at KTH created derivations of the original transparent wood and examined their properties. These innovations are the main theme of this article and suggestions of their use in building industry are presented.

2. Lignin-Retaining Transparent Wood and Its Suggested Applications for Various Types of Transparent Wood Beams

In 2017, researchers at KTH have invented a process of creation of transparent wood, which is leaving the lignin inside the wood cells by modifying its structure and only removing chromophoric structures. The process started by exposing balsa wood to alkaline H_2O_2 treatment. After 0.5 hour, the brightness of wood samples increased to 77% and after an hour it reached 79%, which was acceptable for creation of transparent wood. Longer process did not increase brightness more than to 80%. With delignification process, in contrast, it took 6 hours to get 80% brightness. Samples of delignified and lignin modified wood appeared similar. The large sample of balsa wood with dimension of 100x100x3mm was prepared in 5 hours using a new method, while it took 24 hours with the delignification process. Leaving the lignin in wood has also another benefit. Absence of lignin weakens the wood structure, so handling and fabrication of large samples becomes challenging and unpractical and some species, pine, for example, breaks into pieces when delignified. The polymer infiltration was the same process as the previous one using PMMA. [4]

Mechanical properties of the lignin-modified wood proved to be better compared to delignified samples. Measured wet strengths for various samples are shown in Table 1. [4]

Table 1. Comparisons of two methods (delignification method and lignin modification method) to prepare the wood templates from various wood species for transparent wood fabrication [4].

Wood Species	Treatment Method(s)	Time (h)	Weight Loss (wt%)	Lignin Content (wt%)	Wet Strength(a) ∥ Fiber (MPa)	Wet Strength(a) ⊥ Fiber (MPa)
Balsa	Lignin modification	2	12	21.3	7.9±1.2	0.2±0.09
	Delignification	6	26.4	2.5	6.9±1.3	0.2±0.04
Birch	Lignin modification	2	10.6	20.1	14.4±3.3	0.8±0.2
	Delignification	12	25.3	3.3	1.4±0.4	0.07±0.03
Pine	Lignin modification	8	25.0	22.3	14.4±2.2	0.1±0.02
	Delignification	18	40.9	5.2	(b)	(b)
Ash	Lignin modification	4	15.5	22.4	13.9±1.4	0.2±0.05
	Delignification	18	31.1	5.3	0.8±0.3	(b)
Basswood Thickness ∥ fibre	Delignification and Bleach	12	-	≈ 1.5	-	-
Basswood Thickness ⊥ fibre	Delignification and Bleach	6	-	≈ 1.5	-	-
Cathay Poplar	Delignification and Bleach	16	-	-	-	-

(a) For mechanical test, the samples are cut into dimension of 50 mm×10 mm×1.5 mm before chemical treatment. (b) The samples are too weak to keep the shape for the test. Lignin content of the original wood: pine: 32.5wt %, birch: 24.2wt %, balsa: 23.5wt %, ash: 27.1wt %.

Lignin-retaining transparent wood demonstrated high optical performance. The evaluated sample was of 1.5mm thickness and its optical transmittance was 83%. Its value of haze was 75%. Values for delignified sample were also measured for comparison. Optical transmittance of delignified sample was

86% and its haze was around 68%. Scientists at KTH have speculated that the increased haze values in lignin-retaining transparent wood may be caused by the comparably large refractive index mismatch between lignin (1.61) and PMMA (1.49). [4]

At KTH they also ran a 3-point bending test to assess whether transparent wood could replace glass in structural applications. The stress at breakage was comparable for both. For transparent wood it was at 100.7±8.7MPa and for glass it was 116.3±12.5MPa. Strain to failure went even much better for transparent wood (2.18±0.14%) than for glass (0.19±0.02%). It is thanks to reinforcing wood template skeleton in transparent wood. [4]

These properties of lignin retaining transparent wood can be useful in applications of transparent wood beams. Various types of such beams can be created. To use transparency at the highest level, the optimal option is to create some transparent wood "I" beams. The web of the beams would be made of thin but relatively tall transparent wood with retaining lignin. Flanges would be made of thick and short lignin retaining TW. The beam is illustrated in figure 1. [7]

Figure 1. Transparent wood "I" beam rendering [7].

Another variation is creating some box beams. Such beams would be relatively similar to "I" beams, but they would contain two parallel webs, making the beams less transparent, but stronger. To reinforce the beams even more, while sacrificing some more transparency, Vierendeel box beam is the next option. Such beam would be created as Vierendeel truss set up with thick lignin retaining TW with webs of thin TW fixed at its side. The Vierendeel box beam is illustrated in figure 2. [7]

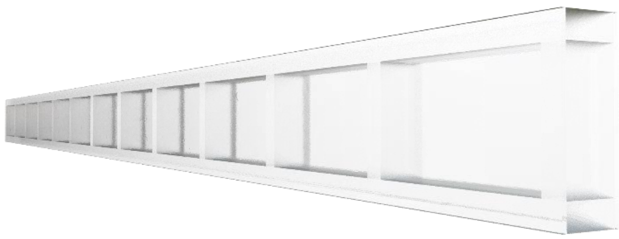

Figure 2. Transparent wood Vierendeel box beam rendering [7].

Yet another option is to create trusses of lignin retaining transparent wood. For this case there are multiple options, of course, but the lightest version is to only use one flange made of TW and the flange would be stretched by a steel cable. The heavier versions would be all TW trusses using thick members of lignin retaining TW as is illustrated in Figure 3. [7]

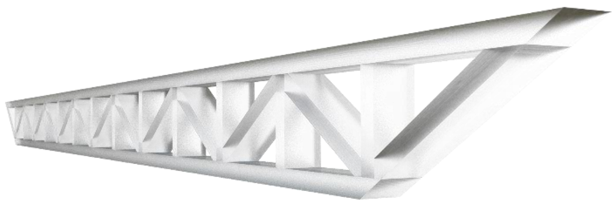

Figure 3. Transparent wood truss rendering [7].

3. Highly Transparent Wood and Its Possible Applications as Façade Material

In 2018, at KTH, they have tried to improve optical transmittance of transparent wood. For this case they acetylated delignified wood samples, using acetic anhydride, for better compatibility with PMMA. It was because wood, especially delignified, is hydrophilic in nature, while polymers as PMMA or epoxy are hydrophobic, which leads to compatibility issues. To obtain the optimized parameters for the acetylation, a systematic study was conducted. Samples with dimensions of 25x25x1.5mm were used for the study.

After acetylation, optical properties of transparent wood improved. For the 1.5mm thick template, optical transmittance reached 92 ± 1%, while the same thickness non-acetylated transparent wood had its optical transmittance of 83 ± 2%. For the neat PMMA it is 95%. Also, wood texture was not obviously visible in the acetylated transparent wood sample. Improvement in optical transmittance was even more visible in thicker samples. While the value of optical transmittance for 3mm thick acetylated transparent wood sample was 89%, it was only 60% for non-acetylated sample of the same thickness. Acetylation also lowered optical haze of transparent wood. For 1.5mm thick samples, optical haze decreased drastically from 70% to 50% and decrease was even larger for 3mm thick samples from 78% to 53%. The haze was still much higher compared to neat PMMA. Comparing two sets of transparent wood samples with 1.5mm thickness (one set always contains acetylated and non-acetylated TW sample of the same cellulose volume fraction), of which one of them had cellulose volume fraction of 30% and other had cellulose volume fraction of 5%, it was found that the increase of optical transmittance for sample with 30% cellulose volume fraction is from 64% to 90%. For the 5% cellulose volume fraction sample it was the increase from 83% to 92%. [5]

Another tests considering highly transparent wood were done on samples with thicknesses of 1.5mm, 3mm, 7mm and 10mm. Optical tests showed that with higher thickness, optical transmittance decreases and haze increases, but compared to non-acetylated samples it is significantly improved. The transmittance of 10mm thick acetylated sample was 40%, similar to 3mm thick non-acetylated sample. Haze increased from 50% in 1.5mm thick acetylated sample to 70 % for the 10mm thick sample. [5]
This higher transparency, which was achieved can be very well used to create transparent wood façades. The factor that is to be considered here, aside from transparency, is thermal conductivity of the material. It can be speculated, that if we used beech to create transparent wood with cellulose volume fraction of 30%, its thermal conductivity would be somewhere around 0.17W/mK (as the thermal conductivity of PMMA is 0.18W/mK and thermal conductivity of beech is around 0.15W/mK). If it is taken into consideration, that after 2021, the U value of windows will have to be 0.6W/m^{2}K, then the thickness of a solid transparent wood façade would have to be around 285mm, which is impossible thickness to achieve, as a 10mm thick sample only has transparency of 40%.

To create TW façades, an inspiration must be taken from double and triple glazing systems in order to make them valid as a construction material. To make the façade system as transparent as possible, 1.5mm thick transparent wood panes should be used. Double pane transparent wood façade with a usual 16mm thick layer of argon would have a U value of 1.1W/m^{2}K. To satisfy the current standard 18mm thick layer should be used, but to reach the standard after 2021, a 30mm thick layer of argon would have to be used. It is different with krypton, as only 17mm thick layer would satisfy the standard after 2021. To satisfy the current standard, only 10mm thick layer of krypton would be necessary. The usual thickness of krypton layer in glazing systems is 12mm, which makes TW façade's U value of 0.82W/m^{2}K.

Triple pane transparent wood façade with usual 16mm thickness of argon layers would have its U value of 0.55 W/m^{2}K. This is even more efficient than the standard after 2021 requires. To satisfy this standard, only 15mm thick layers of argon are necessary. For the current standard it would only be 9mm thick layers of argon. With the usual 12mm thick layers of krypton in a triple pane transparent wood façade system, the system would have its U value of 0.41 W/m^{2}K. For the satisfaction of the standard valid after 2021, only 9mm thick layers of krypton would be necessary and to satisfy the current standard only 5mm thick layers of krypton would be required. All the options of façade set ups mentioned above are summarized in table 2.

Table 2. Summary of U values of different transparent wood façade set ups.

Facade type	Thickness of layer(s) (mm)			U (W/m^{2}K)
	Transparent wood	Ar	Kr	
Solid wall	170	-	-	1
	285	-	-	0.6
Double pane	2x1.5	16	-	1.1
	2x1.5	18	-	0.98
	2x1.5	30	-	0.59
	2x1.5	-	10	0.98
	2x1.5	-	12	0.82
	2x1.5	-	17	0.58
Triple pane	3x1.5	2x9	-	0.97
	3x1.5	2x15	-	0.59
	3x1.5	2x16	-	0.55
	3x1.5	-	2x5	0.97
	3x1.5	-	2x9	0.55
	3x1.5	-	2x12	0.41

(light orange) satisfies current EN standard
(light yellow) satisfies EN standard after 2021
Thermal conductivity of transparent wood was considered as 0.17W/mK

4. Transparent Plywood and Solid Building Systems

It was created at KTH using delignified veneers, which were compressed by the force of 75kN for 25 minutes under 25°C after delignification. These delignified compressed veneers were then infiltrated by PMMA and turned transparent. Then they assembled five layers of transparent veneers in perpendicular direction to each other (0/90/0/-90/0, cp-TPW) and also assembled other five layers in a quasi-isotropic structure by increased 45° (0/45/0/-45/0, qi-TPW). These layers were then laminated, again using PMMA. [6]

Both, optical and mechanical properties of transparent plywood were evaluated. The findings are as follows. Unlike regular transparent wood, transparent plywood displays isotropic optical properties. Optical transmittance for cp-TPW with the thickness of 3.0 – 3.5mm is 83%. For qi-TPW with the same thickness it is 75%. Single ply TW with the thickness of 0.8mm has the same optical transmittance as a pure PMMA with the thickness of 3mm having the value of 90% – 95%. Optical haze is for both types of TPW at a value of 80%. Single ply TW has the haze of around 50% - 60%. For the PMMA, the haze is lower than 5%. [6]

A setup was designed and built for the measurement of transmitted light intensity to study the scattering behaviour of TPW. The scattering patterns and light intensities of single ply TW and qi-TPW at different angles were observed. It was found that the scattered light distributions of single ply TW are different between L and T directions. This is caused by anisotropic structure of wood. In contrast, the scattered light distribution in qi-TPW is almost homogenous. [6]

Mechanical tests of TPW revealed that the ultimate strength for single ply TW increases linearly with cellulose volume fraction. Table 3 summarizes the mechanical properties of single ply TW and TPW. [6]

Table 3. Summary of the mechanical properties of single ply and TPW, and the Young's modulus predictions from laminate theory [6].

Wood Species	Tensile Test Direction	Cellulose Volume Fraction (%)	Size	Mechanical Properties			
			l x w x t (mm)	E (GPa)	E^a (GPa)	σ (MPa)	$\varepsilon_c \approx$ (%)
Single Ply	L	12	60x5x0.8	4.3 ± 0.4	-	62.5 ± 2.7	1.5
TW	T	12		2.4 ± 0.2	-	14.6 ± 1.2	0.7
Cp-TPW	L	10	60x5x3.5	4.1 ± 0.3	3.7	50.1 ± 2.6	1.2
	T	10		3.9 ± 0.1	3.3	44.9 ± 1.3	1.3
Qi-TPW	L	10	60x5x3.5	3.9 ± 0.2	3.4	45.4 ± 2.9	1.2
	T	10		3.5 ± 0.3	3.0	42 ± 1.8	1.4

'-': No data available. 'l × w × t': Length, width and thickness, respectively. 'E': The Young's modulus from the experimental data. E^a: The predicted Young's modulus is determined based on laminate plate theory. 'σ': Ultimate strength. 'ε_c': Failure at break. '*': T The mechanical performance values were calculated from tensile test with AVE.

Transparent plywood could find its purpose in building industry as semi-transparent non-bearing partition walls or as load bearing solid beams for short bridges or for stairs, which would also act as railings (figure 4). If the thicker samples were created, they could be arranged similarly to cross laminated timber and would be able to span even further distances.

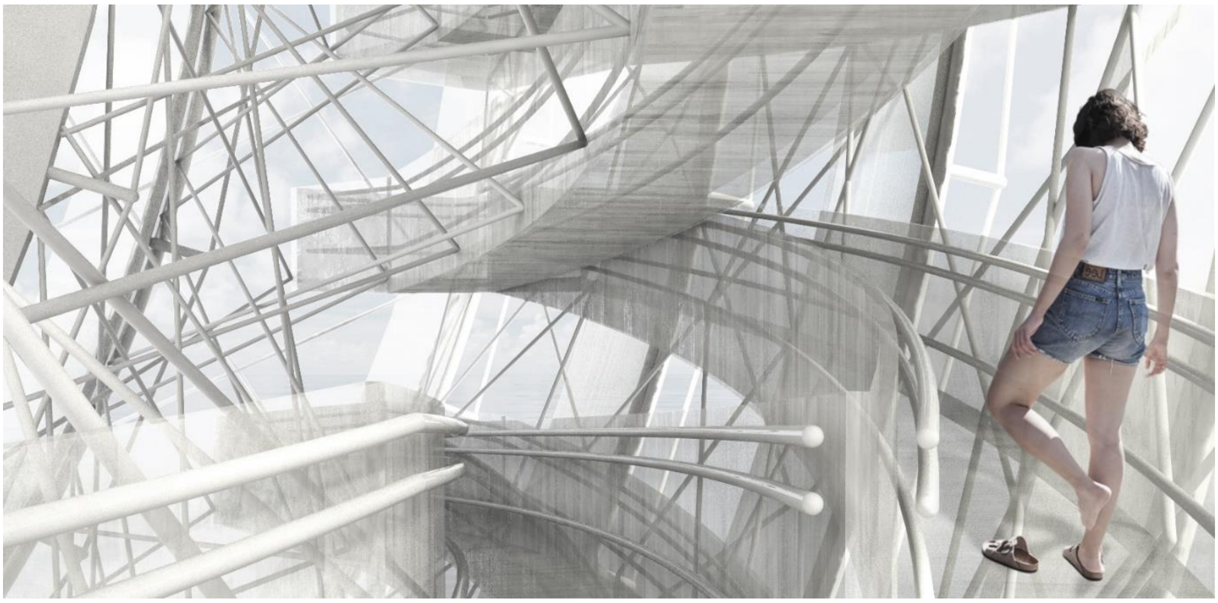

Figure 4. Rendering of transparent wood solid beams/railings used for ramps at Tathra Beacon (designed for MNPG Arch competition).

Also, panel building systems can be considered using transparent plywood (or transparent cross laminated timber), where TW panels would be at the outer surfaces of the panel and inside, the panel would be insulated with aerogel and reinforced with transparent wood grid made of thick TW members, so the structure would be all transparent with sufficient thermal resistance. Such system is illustrated in figure 5.

Figure 5. Rendering of transparent wood + aerogel panel system

5. Conclusions

The research on transparent wood has only begun recently, but it is already advancing rapidly, as was shown in this article. With improvements in technology of fabrication of transparent wood, it is becoming more ecologically friendly and more easily obtained material with lignin-retaining transparent wood. With acetylation, transparent wood optical properties become even more attractive and thicker samples can be created as the research on highly transparent wood has shown. Finally, transparent plywood made properties of otherwise highly anisotropic material isotropic and transparent plywood showed even better structural properties than, before also outstanding, original transparent wood composite. One can speculate about its future possible applications as façade material, probably mostly in situations where there is required sunlight just as much as privacy, as its high optical transmittance together with high optical haze predetermine it. As was shown, compared to glass systems, transparent wood facades would require less material and lesser amount of inert gases, therefore would also save more money. Another speculations considering this material are to use it structurally as a load bearing material due to its mechanical properties in various types of beams, namely “I” beams, box beams and various forms of trusses, or even as a glued solid beam. What the future holds for transparent wood is uncertain now, but the possibilities of future architectures are exciting for sure.

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