Analysis of mechanical properties of I-beam with web from transparent wood

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Abstract. This article contains a brief information about history of transparent wood, its fabrication process and its physical and mechanical properties. The main goal of this article, however, is to find whether transparent wood is a suitable material for load-bearing architectural constructions. This is achieved by using numerical analysis of I-beam with web from transparent wood (and various types of it) and comparing its results with the same sized beam with web from OSB (oriented strand board) and web from glass, which are both successfully used for such applications nowadays. Suggestions on how to use transparent wood as a load-bearing material are also presented in the article.

1. Introduction
Transparent wood was first mentioned in the article Transparent Wood - A New Approach in the Functional Study of Wood Structure by German scientist Sigfried Fink in 1992 [1]. In his research, he produced transparent wood samples in order to better observe specific three-dimensional wood structures. In his experiment, he was inspired by Spalteholz, who in 1914 introduced a technique to make coarse body organs transparent for analytical purposes using organic liquids with appropriate refractive indices.

Between 2015 and 2016, two teams at the Swedish KTH and the University of Maryland rediscovered Fink's article, began researching the properties of transparent wood and designed its possible applications for lightweight low-cost structures in light-transmitting buildings, solar cells, furniture or as construction material in cars and optoelectronics [2][3]. While in Maryland their research on transparent wood is part of the ongoing research on super-wood structures, in KTH they focus exclusively on transparent wood, thus have published more articles on this topic and have come up with interesting innovations with regard to its fabrication concepts and improvements of its properties.

In this paper, a numerical analysis of the mechanical properties of transparent wood with various parameters compared to other commonly used materials is published in a model example of a composite I-beam with flanges of natural wood in order to verify the suitability and efficiency of its use as a load-bearing building material.
2. Characteristics of transparent wood

2.1. Transparent wood fabrication
The fabrication of transparent wood consists of two steps. The first is removal or modification of lignin and the second is impregnation of the delignified sample with a transparent polymer. In KTH, delignification was achieved using a 1% sodium chlorite solution (NaClO2) with an acetate buffer solution (pH 4.6) at 80 °C. The delignified samples were then purified in deionized water. They were then dehydrated. Initially, with pure ethanol and then with a 1:1 mixture of ethanol and acetone. After the delignification was complete, a prepolymerized methyl methacrylate (MMA) solution was infiltrated into the wood under vacuum [2]. In Maryland, delignification was a two-step process. The first step was to put the wood samples into a boiling solution of sodium hydroxide (NaOH) and sodium sulphate (Na2SO3). This was followed by placing of partially delignified samples into a solution of hydrogen peroxide (H2O2) to remove the remaining lignin. Subsequently, the epoxy resin was infiltrated into the delignified wood by repeated vacuum and de-vacuum [3]. In addition, in KTH they were further modifying the delignification process, which was criticized for the use of aggressive chemicals, leading to a not very ecological process for producing transparent wood. Instead of completely removing the lignin, the modification procedure was chosen using deionized water, sodium silicate Na2SiO3 (3.0 wt%), sodium hydroxide solution NaOH (3.0 wt%), magnesium sulphate MgSO4 (0.1 wt%), DTPA of diethylenetriaminepentaacetic acid (0.1 wt%) and finally hydrogen peroxide H2O2 (4.0 wt%). The wooden samples were then immersed in a solution heated to 70 °C until the veneers became pale. The samples were then thoroughly washed with deionized water and stored in water until further use. Subsequently, the PMMA infiltration process was identical to their previous procedure [4].

2.2. Mechanical and physical properties of transparent wood
So far, only thin samples of transparent wood have been produced. Scientists mainly examined their optical and mechanical properties. From these studies we know about the following findings.
Transparent wood of different thicknesses exhibits different optical properties. The thinner the sample, the higher its optical transmittance. This is because transparency depends on the volume fraction of cellulose. At KTH, the highest optical transmittance was achieved with a 0.7 mm thick sample and it was 90%. The lowest value was approximately 40% for a 3.7 mm thick sample [2]. In Maryland, researchers focused on how the properties of transparent wood depend on the cut of the original wood, meaning that they studied the properties of radially and longitudinally sawn wood. As radially sawn wood has a lower volume fraction of cellulose, it achieved 90% optical transmittance with a 2 mm thick sample and approximately 80% with the same thickness of longitudinally cut wood. Another optical feature studied by both universities is the optical haze of the samples. [3] At KTH they measured 60% to 80% haze values, with higher values in thicker samples. In Maryland, they measured a haze of 90% for longitudinally sawn wood and surprisingly close to 100% for radially sawn wood. Radially cut wood has a lower volume fraction of cellulose, but an important factor here is the arrangement of the wood cells that have produced a higher haze [3]. In a greener version of transparent lignin-modified transparent wood at KTH, they found that a 1.5 mm sample had an optical transmittance of 83% (equally thick delignified sample 86%) and a haze of 73% (equally thick delignified sample 68%) [4].

Transparent wood also has excellent mechanical properties. At KTH they found that they are better for transparent wood than for natural wood and PMMA. The modulus of elasticity for transparent wood with a 5% cellulose content was 2.05 ± 0.13 GPa (i.e. 1.80 ± 0.18 GPa for PMMA and 0.22 ± 0.08 GPa for delignified wood). Transverse tensile tests of transparent wood with a total volume fraction of 19% measured its tensile strength of 90.1 ± 10 MPa with a modulus of elasticity of 3.59 ± 0.27 GPa (for PMMA it was 44.1 ± 9.5 MPa) [2]. In Maryland, they also examined the mechanical properties of the samples and found that both radially sawn and longitudinally sawn woods are stronger than their natural counterparts and that transparent longitudinally sawn wood has approximately twice the strength of transparent radially sawn wood (table 1) [3]. In the case of transparent lignin-modified wood, the strength was found to be even higher than that of lignin-depleted samples (100.7 ± 8.7MPa) [4].
Table 1. Comparison of mechanical properties of natural radially sawn wood, natural longitudinally sawn wood, transparent radially sawn wood and transparent longitudinally sawn wood [3].

|                        | Strength (MPa) | Modulus of elasticity (GPa) | Toughness (MJ/m²) |
|------------------------|----------------|-----------------------------|-------------------|
| Natural radially cut wood | 4.46           | 0.19                        | 0.10              |
| Transparent radially cut wood | 23.38         | 1.22                        | 0.59              |
| Natural longitudinally cut wood | 42.72         | 5.78                        | 0.33              |
| Transparent longitudinally cut wood | 45.38        | 2.37                        | 1.20              |

3. Suggested usage of transparent wood in the applications of load-bearing constructions

If there is a chance to produce large pieces of transparent wood, we can simply use those and make some type of bearing structural elements, as beams, trusses etc. The problem is that elements produced from massive transparent wood will not transmit enough light and are difficult to produce. This is the reason to assume that different beams will have to be made using thin, transparent wood elements that can be fabricated and the appearance of the entire structure will be much more subtle and attractive at the end.

One possible option is I-beam, where the web of this beam is made of thin transparent wood and the flanges are made of either natural wood, laminated veneer lumber or thicker transparent wood elements. This is the lightest looking version of transparent wooden beams possible. Architecturally, a structure made with such beams almost seems to be floating or levitating in space, which may be highly desirable.

Figure 1. Rendering of I-beam from transparent wood [5].

Another possibility is to create box beams. They would be formed in a similar way as 'I' beams. The flanges could again be made of natural wood, laminated veneer lumber or thicker transparent wood elements and the webs would be made of thin transparent wood panels. These beams are not so light in appearance (although they still look quite light), but can support more loads.

Figure 2. Rendering of Vierendeel box beam from transparent wood [5].

A variation of this type is the creation of Vierendeel beams (again with the aid of a natural, laminatef or thick transparent wood) with thin transparent wood panels added on both sides. Of all the above mentioned, it is the least light-appearing variant, but the strongest.
Figure 3. Rendering of transparent wood truss [5].

Transparent timber trusses are another way to use transparent wood in construction. Of course, thicker elements will have to be used to make them, but not as thick as one massive beam would require. Such trusses may be entirely of transparent wood, or only a flange would be made of transparent wood and then be coupled with a steel cable to achieve a much lighter construction overall.

There is also a chance to use massive transparent wood beams inspired by parallam beams. Research on such transparent wood elements has shown that their strength is comparable to conventional transparent woody samples (46.8 MPa), while it is easier to achieve greater transparency (10 mm thick – 68%, 1 mm thick – 92%) with lower haziness (10 mm thick – 90%, 1 mm thick – 56%) [6].

4. Numerical model of I-beam with web from transparent wood
ANSYS Workbench 17.2 was chosen for the theoretical analysis (figure 4). 7 types of beams were modelled, differing in the material of the web beam: (1) transparent wood (TW) single-layer (veneer) with fibre orientation in the direction of the beam axis, (2) single-layer TW with fibre orientation perpendicular to the beam axis, (3) 5-layer TW type CP with cover layer orientation in direction of beam axis, (4) 5-layer TW type CP with cover layer orientation 45° to beam axis, (5) 5-layer TW type Qi, (6) OSB, (7) glass. The flanges of the I-beam were of massive natural wood. In numerical analysis, natural wood, OSB and glass were modelled as linear elastic isotropic material, transparent wood as linear elastic orthotropic material. The material properties used are listed in table 2. Data for mechanical properties of transparent wood were obtained from the article Transparent plywood as a load-bearing and luminescent biocomposite [7].

The contact between the web and the flanges was set as "bonded" for all nodes of the connection. Newton-Raphson's iterative method considering large deflection was used for the calculation. Half of the beam was modelled with the symmetry set at the centre of the span. The maximum size of the mesh element was 5.0 mm.
Table 2. Material parameters for numerical analysis.

| Material | Direction   | Modulus of elasticity E (GPa) | Shear modulus G (GPa) | Poisson's ratio μ (-) | Tensile strength f (MPa) |
|----------|-------------|-------------------------------|-----------------------|-----------------------|--------------------------|
| Timber   | longitudinal| 11.0                          | 0.37                  | 0.48                  | 16.0                     |
| TW_veneer| longitudinal| 4.3                           | 1.40                  | 0.37                  | 62.5                     |
|          | transverse  | 2.4                           | 1.00                  | 0.10                  | 14.6                     |
| TW_CP    | longitudinal| 4.1                           | 1.40                  | 0.37                  | 50.1                     |
|          | transverse  | 3.9                           | 1.00                  | 0.10                  | 44.9                     |
| TW_Qi    | longitudinal| 3.9                           | 1.40                  | 0.37                  | 45.4                     |
|          | transverse  | 3.5                           | 1.00                  | 0.10                  | 42.0                     |
| OSB      | -           | 3.8                           | 1.08                  | 0.30                  | 9.9                      |
| Glass    | -           | 70.0                          | 28.70                 | 0.22                  | 20.0                     |

5. Comparison between I-beams with web from transparent wood, OSB and glass
The beams were loaded with the uniform area load of 0.012 MPa which is corresponding to 1.0 kN/m of beam load. The calculated deflection values at the middle of the span of the timber-based beams are compared in figure 5. The differences between the deflections are relatively small, but the smallest deflection was calculated for sample no. 4 with a 5-layer transparent wood with a 45° inclination relative to the beam axis.

Further results of the numerical analysis are shown in table 3. The glass-web beams had a deflection up to 33% less than the wood-based beams, but the normal stress was relatively high due to the tensile strength of the glass.

Figure 5. Calculated deflection of I-beams with various web type.

Table 3. Results of numerical analysis.

| No. | Material of web | Deflection (mm) | Max normal stress $\sigma_x$ (MPa) | Tensile strength f (MPa) | $\sigma_x / f$ (%) | Max shear stress $\tau_{xy}$ (MPa) |
|-----|-----------------|-----------------|-------------------------------------|--------------------------|-------------------|-------------------------------|
| 1   | TW_veneer_0     | 7.408           | 1.2403                              | 62.5                     | 2.0%              | 1.805                         |
| 2   | TW_veneer_90    | 7.448           | 0.6745                              | 14.6                     | 4.6%              | 1.688                         |
| 3   | TW_CP_0         | 7.388           | 1.1628                              | 50.1                     | 2.3%              | 1.894                         |
| 4   | TW_CP_45        | 7.367           | 1.0931                              | 44.9                     | 2.4%              | 1.845                         |
| 5   | TW_Qi           | 7.400           | 1.1089                              | 45.4                     | 2.4%              | 1.897                         |
| 6   | OSB             | 7.372           | 1.0586                              | 9.9                      | 10.7%             | 1.741                         |
| 7   | Glass           | 4.929           | 15.231                              | 20                       | 76.2%             | 2.122                         |

7.30 7.35 7.40 7.45 7.50
TW_veneer_0 TW_veneer_90 TW_CP_0 TW_CP_45 TW_Qi OSB
Mid-span deflection (mm)
6. Conclusion
Numerical analysis has shown that transparent wood is suitable for use in load-bearing structures, as an I-beam with a transparent wood web of different types has a comparable deflection at the same web thickness as well as a normal stress with an OSB web I-beam. Although the glass-web beam has smaller deflection compared to transparent wood and OSB, its normal stress is already approaching a critical value, while transparent wood and OSB could still bear much heavier loads.

7. References
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