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A REVIEW OF METHODS TO INCREASE THE FLEXIBILITY OF WOOD

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Abstract: *This paper provides a short review of the techniques that can be used to make flexible wood-based products. It also describes preliminary experiments on the potential of radial compression of French grown Poplar (Populus spp.) for the manufacture of highly flexible products. A 50% uniaxial compression strain was applied to wood blocks with an average moisture content of 15.5%. The blocks were then glued together to make larger panels from which small beams (nominally 10 x 10 x 150 mm^3) were cut. After conditioning, the bending properties were measured. None of the flexibilized beams broke during testing and their stiffness was found to be less than 10% of the control beams.*

Key words: *flexible wood, radial compression, poplar.*

1. Introduction

Compared to many materials, wood is already flexible, but inevitably, the markets and man's imagination want even more flexibility. Enhanced flexibility is most often required in order to make molded products, which once made, are normally required to hold their shape, i.e. the flexibility becomes less important or even an inconvenience. Examples include molded chairs, stairway handrails, trays, and so on. Other, less common situations require the wood to remain flexible in use, such as wood curtains, eye-glasses, and some examples of packaging. In this paper, these two different situations will be termed *pre-use* and *in-use* flexibility.

A degree of flexibility can be measured in various ways. A very common measure is the bending stiffness (modulus of elasticity – MOE). One would expect that the lower the stiffness, the greater the observed flexibility, but this is only true if the low stiffness is due to high deflections (strains) during measurement. Low stiffness materials generate lower stresses during bending, but the material must still have sufficient strength to resist the induced stresses. In this paper, a flexible material is one that deforms readily, does not break easily, and returns to its non-

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stressed shape (even if eventually).

Flexible materials are often used to make curved objects, as it is much more efficient to make a curve from a single piece than combining several components. Bending a material induces tensile stress on the outside (convex) of the curve and compression stress on the inside (concave). If either the tensile or the compressive stresses reach the ultimate strength of the material, then the object will break. Consequently, even a flexible material will still break if bent excessively. A bending ratio [7] based on the thickness of the material divided by the radius of the inner bend can be calculated and used as an indicator of flexibility. Alternatively, the minimum bending radius can be expressed in terms of material thickness ().

The flexibility of wood can be improved by chemical modification, mechanical alteration, and/or machining [4], [9-10]. Kutnar et al. provide a good overview of a range of techniques used to create wood shapes by the application of external forces, i.e. not machined into a shape [5].

Table 1

Example minimum bending radii expressed as thickness of the material

Material	Minimum bend radius	Material	Minimum bend radius
Aluminum	0-6t	High Pressure Laminate (cold)	300t
Solid wood (parallel to grain) [4]	50t	High Pressure Laminate (warm)	16t
Beech veneer (perpendicular to grain) [7]	35t	Norway spruce veneer (perpendicular to grain) [7]	47.5t
Bendywood [14]	10t	Oak veneer (perpendicular to grain) [7]	46t
Birch plywood (parallel to face grain) [10]	115t	Softwood plywood (parallel to face grain) [10]	180t
Birch plywood (perpendicular to face grain) [10]	108t	Softwood plywood (perpendicular to face grain) [10]	130t
Brass	0.1-2t	Stainless steel	0.5-1t
Copper	3-4t	Steamed hardwood [9]	1-5t
Glass	>1,000t	Steamed softwood [9]	14-30t

2. Chemical Modification

2.1. Steam Bending

The steam bending of wood has been used for well over a century to obtain curved solid wood elements that are not possible at room temperatures and moisture contents. The objective of steaming is to change the mechanical properties of wood rather than its chemistry, but it is inevitable that the chemistry changes, even if it is only the evaporation of some extractives, and so it is included in the chemical modification section.

Traditionally, steaming is done at near atmospheric pressure, i.e. 100 °C. The wood is heated until its moisture content is around 15-17%. It is then placed in a mold and bent with a metallic support strap on the convex face. The wood is left to cool and dry for a number of hours. The mechano-sorption processes that take place relax the stresses present in the wood so that when the mold is opened, the wood exhibits little spring-back. This technique has been used to make furniture like that shown in Figure 1 for many years.

Fig. 1. An example of steam bent wood used in traditional furniture made by Ercol

Generally it is the thickness of the section of wood to be bent that determines the steaming time. Approximately 3 minutes per millimeter of thickness is required to soften hardwood sufficiently to permit safe bending with minimal breakages [13] and 1 minute per millimeter for softwoods [6]. Excessive heating can lead to an increase in the number of compression and tension failures because the mechanical properties of the wood are also reduced.

Once steamed-wood has cooled and dried, it has the same rigidity of normal wood. Sometimes its mechanical properties are seen to improve in the bend area due to densification of the wood. Steaming does not, therefore, make flexible products, rather it facilitates 2 and 3 dimensional deformation for a short period, i.e. this is an example of *pre-use* flexibility.

2.2. Liquid and Gaseous Ammonia

Wood can be plasticized using anhydrous ammonia gas [8], anhydrous liquid ammonia [1] or ammonia solution [10]. Ammonia causes more swelling in wood than water. The volumetric swelling of beech (*Fagus sylvatica*) is about 120% of that caused by water [1]. This leads to enhanced creep and reduced stiffness. Consequently, ammonia treated wood is much more flexible and can be contorted into a range of weird and wonderful shapes. The ammonia soon evaporates from the wood, which regains its original stiffness but remains deformed. A darkening of the wood if often observed too (Figure 2).

Fig. 2. *Examples of bent wood artefacts made by plasticizing wood with ammonia solution*

Ammonia is not a pleasant compound, having a very pungent odor. Many more precautions are needed when using ammonia rather than steam to bend wood. Although more extreme bends are possible with ammonia, in most cases steam bending is sufficient.

2.3. Machining

Stresses are induced in a piece of wood when it is bent by an external force. Tensile stresses are generated in the convex (outside) face and compression stresses in the concave (inside) face. Logically there is a neutral plane in the center where the tensile and compressive stresses balance each other out. The piece will break if either the tensile or the compressive stresses exceed that of the wood. The force required to bend an object is directly linked to its thickness, i.e. thicker pieces are more difficult to bend. This is clearly shown by the equation used to calculate the stiffness of an object in 3-point bending as the MOE increases with the cube of the thickness:

$$E = \frac{L^3 \cdot F}{4 \cdot w \cdot t^3 \cdot d}. \tag{1}$$

where:

E is bending stiffness; L - span;
F - force applied; w - width;
t - thickness; d - deflection.

The equation can be re-arranged so that the force required to achieve a specific deflection in a given situation can be calculated as follows:

$$F = \frac{E \cdot 4 \cdot w \cdot d}{L^3} \cdot t^3 \tag{2}$$

This equation shows very clearly that the force needed to bend a particular material changes with the cube of its thickness. So if the effective thickness of a material in a given situation is halved, then the force needed to achieve the same deflection is reduced to 12.5%, i.e. 0.5^3 of what it was before. This is the principle behind using machine cuts to make flexible products. The incisions also provide empty space that allows the concave face to displace without creating additional stresses (Fig. 3).

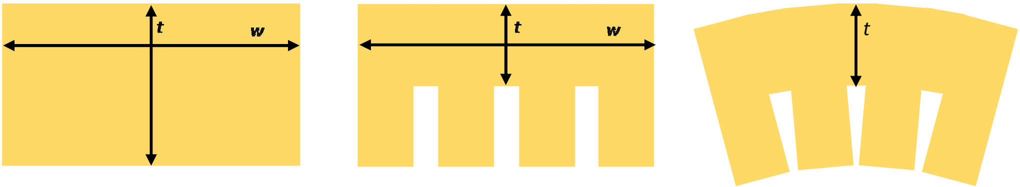


Fig. 3. *Reducing the effective thickness of material significantly reduces the force needed to bend it*

Fig. 1. *Examples of the Dukta product (source: dukta.com)*

Dukta manufacture a range of products including art objects, light fittings, and acoustic panels that are based on the concept of making precise incisions in solid wood and composite products (see https://dukta.com/). The cuts are cleverly designed to enhance the "look" of the product and give an astonishing degree of *in-use* suppleness ().

The availability of relatively inexpensive computer controlled laser cutting and engraving machines has generated a plethora of flexible wood products, many of which have a very pleasing look created by the complex and varied patterns used to achieve the flexibility.

2.4. Mechanical Alteration

The product called Bendywood® is manufactured by Candidus Prugger in Italy. The process is based on a patent originally published in 1917. In summary, the wood is heated with saturated steam so that it has the correct moisture content and temperature to give uniform cell wall rupture when the piece is compressed longitudinally. The piece must be clamped along its length to avoid any buckling and bending stress. After pressing, the product is dried. The mechanical damage caused during the pressing phase creates creases in the fibers that are rather like the pleats in a bendable plastic straw. Consequently, the wood is more flexible; perhaps 5 times more flexible, as indicated in .

Bader (2017) studied the longitudinal compression method for flexibilizing wood and presented his results in the previous meeting of ICWSE [2]. The process requires that the wood be wet, preferably at the fiber saturation point, and hot, so steam heating is used. His data shows that the bending stiffness is more affected than the bending strength, and this permits more extreme bending than is possible for solid wood.

Hirano et al. (2016) demonstrated an alternative approach to achieving flexible wood through inducing compression damage [3]. The main difference is that the compression strain is applied radially to the wood. This implies that only short pieces of wood can be compressed and these then have to be glued together. The process is long and somewhat complicated, but very flexible wood products are possible.

Wehsener et al. (2014) also used transverse compression and gluing to make panels with high degrees of flexibility, but they added different types of textile to provide reinforcement [12].

The aim of the experiments presented below was to conduct an initial investigation into the potential use of French grown Poplar for the manufacture of flexible wood products.

3. Materials and Methods

Blocks of poplar (*Populus spp*) nominally 62 mm long, 27 mm wide (tangential direction), and 27 mm thick (radial direction) were cut and conditioned to give a moisture content of 15.5%. The thickness of the blocks was reduced by 50% at room temperature using the compression plates of a universal testing machine as shown in . The faces of the blocks were then sanded lightly to improve gluing. Next, 9 blocks were selected at random to create a panel which were glued together using a D3 grade PVAc emulsion. One face and one edge of the ends of the subsequent panel were sanded smooth and flat. The panel was then cut in half to provide 2 pieces approximately 60 mm wide (parallel to grain), 10 mm thick (tangential direction), and 165 mm long (radial direction). After sanding, these were then cut into small beams nominally 10 mm wide, 10 mm thick, and 165 mm long.

Control beams were manufactured in the same way, but with blocks of Poplar that had not been compressed. Since their thickness had not been changed, only 6 blocks were needed to give beams of a similar length.

The beams were conditioned for 1 week before testing in 3-point bending with a span of 100 mm and a test speed of 10 mm/min for the flexible beams and 2 mm/min for the control beams. The average moisture content of the beams at the time of the test was 13.3% OD basis.

The beams were tested in two modes such that the wood grain was either vertical (parallel) or horizontal (perpendicular) to the applied strain (see). The beams were tested in sequence so that each neighbouring specimen in the original panel was tested in the other sense.

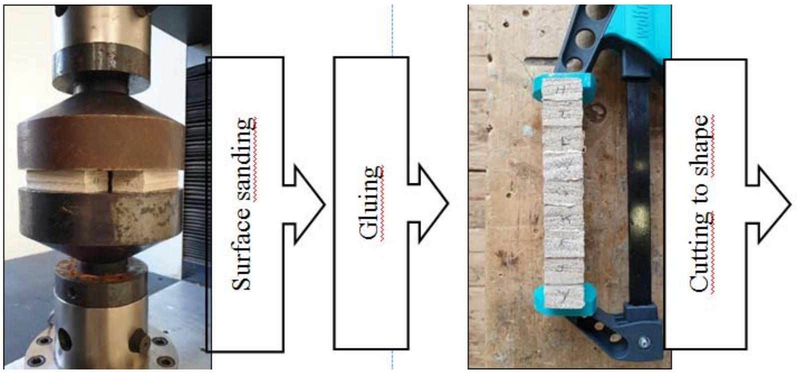
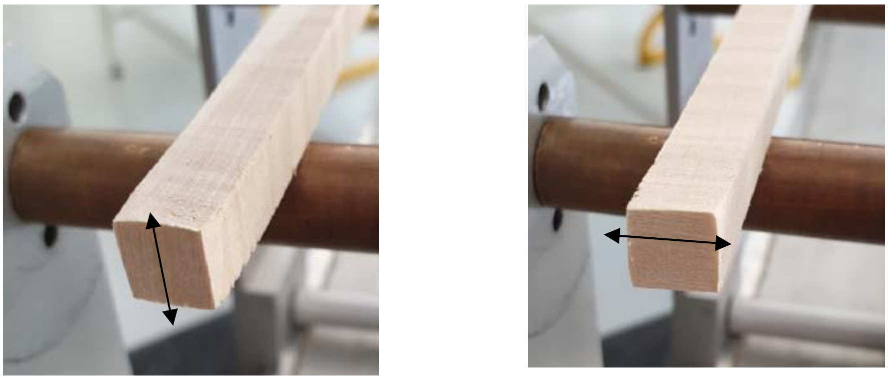


Fig. 5. *Outline of the manufacturing method*



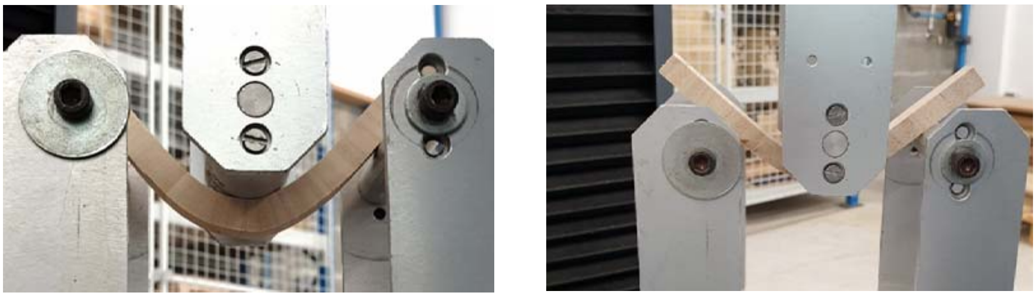
Parallel to grain *Perpendicular to grain*

Fig. 6. *Compression stress was applied in the middle of the beams so that the stress was either parallel to the grain (left) or perpendicular to the grain (right). Note that the arrows indicate the grain direction during the test*

Some of the beams were examined with a Quanta 250 Environmental Scanning Electron Microscope (ESEM) made by FEI. Pieces of beam were placed in a micro-mechanical testing machine installed within the vacuum chamber of the ESEM and stretched to different strains in order to observe the deformation of the individual cells.

4. Results

The peak stress required to compress the wood blocks (Figure 7) to half their thickness was consistently around 7.0 MPa. The springback of the blocks approximately 2 minutes after pressing was found to be approximately 33% ± 2% of the pressed thickness (13.65 mm). The average density of the blocks increased from 367 kg/m^3 to 529 kg/m^3 after pressing and initial springback.



Parallel to grain *Perpendicular to grain*

Fig. 7. *Compression stress was applied in the middle of the beams so that the stress was either parallel to the grain (left) or perpendicular to the grain (right)*

The flexibility of the wood became apparent once cut into small beams as it was very easy to flex them both parallel and perpendicular to the grain. The data from the 3-point bending tests, shown in Table 2, provides a quantitative indication of the changes in the flexural properties brought about by compressing wood radially. None of the flexibilized beams broke during bending. The MOR is, therefore, calculated using the peak force observed during the test.

From Table 2, it is clear that the mechanical properties of the beams are significantly lower when made from compressed wood blocks. Interestingly, the stiffness in both test modes was reduced by about 91%, whereas the bending strength was reduced in the range of 69 to 73%. The ideal would be to reduce the stiffness with minimal impact on the bending strength; a series of optimization experiments are needed to find the optimum. A Students t-test indicates that the MOR of the flexibilized beams is stronger in the parallel direction compared to the perpendicular (98% confidence); however, there is no statistical difference between the MOE values obtained from each direction.

Data estimated from a graph of results presented by Hirano et al. (2016) of flexibilized Sugi (*Cryptomeria japonica*) indicates that they observed a similar MOR of around 2.9 MPa, but a lower MOE of approximately 35 MPa, which is quite similar to the data presented here [3]. According to the Tropix database, Sugi typically has a density of 380 kg/m^3, which is a little lower than that for Populus species (450 kg/m^3), and this difference may explain their findings.

Table 2

The bending characteristics observed in small beams made from laminated poplar

	Perpendicular	Parallel
Flexibilized wood		
Mean MOE [MPa]	67.7	72.6
Standard deviation of MOE [MPa]	3.6	9.8
MOR at peak force [MPa]	2.9	3.2
Standard deviation of MOR [MPa]	0.2	0.2
Number of tests	8	8
Control		
Mean MOE [MPa]	798.6	856.4
Standard deviation of MOE [MPa]	67.3	75.2
MOR [MPa]	10.9	9.6
Standard deviation of MOR [MPa]	0.3	0.8
Number of tests	3	4

The microscopic examination of the flexibilized wood beams revealed the presence of rupture zones created during the compression phase of the manufacturing process. The cell walls in these zones are severely damaged, see . It was observed that the most obvious deformations occur in these failure zones on the application of tensile strain. The broken cell walls provide the mechanism for the flexibility observed, as relatively large strains can be applied without generating high stresses in the cell wall material, thus avoiding fracture.

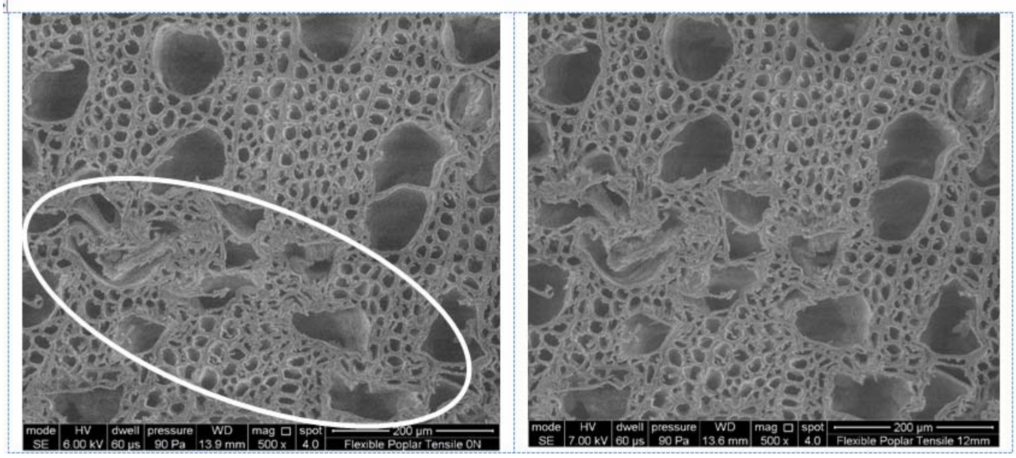


Fig. 8. *Electron micrographs of flexibilized poplar. Left: No strain applied, Right: 1.2 mm of tensile deformation applied (approximately 10% strain). White ellipse marks main zone of change*

5. Conclusions

A radial compressive strain of 50% applied to solid Poplar wood blocks creates failure zones within the wood. These zones also increase the quantity of tensile strain that can be applied to the wood before failure occurs. Gluing together several compressed blocks permits the fabrication of long and very flexible beams.

Further studies are required to optimize flexibility whilst minimizing the impact on the ultimate mechanical properties.

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