Construction and Building Materials 73 (2014) 171–179

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Impact of internal structure on water-resistance of plywood studied using neutron radiography and X-ray tomography

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HIGHLIGHTS

- We use neutron radiography to measure the water transport in plywood and solid wood.
- We use X-ray CT to investigate the internal structure of the samples.
- Moisture transport behaviour of plywood is analysed based on its internal structure.
- Apart from wood, veneer checks and gaps also influence water resistance of plywood.
- Adhesive and grain direction of the veneers impact moisture resistance of plywood.

ARTICLE INFO

Article history:
Received 22 April 2014
Received in revised form 10 September 2014
Accepted 24 September 2014

Keywords:
Neutron radiography
X-ray tomography
Water resistance
Wood structure
Plywood

ABSTRACT

To improve water resistance of plywood, a detailed understanding of the moisture dynamics of plywood and related solid wood is essential. Neutron radiography and X-ray CT were used to monitor water transport and the internal micro-structure respectively. Compared with solid wood, water uptake and release of plywood is, apart from wood species, also influenced by veneer checks and gaps between veneers. Type of adhesive and grain direction of veneers also play a crucial role. According to the findings of this paper and practical requirements, more water resistant plywood can be produced when taking into account abovementioned factors.

1. Introduction

Wood is an important construction material with the advantage of being ecological sustainable and flexible in usage [1]. However, as a bio-material, moisture can decrease its physical, mechanical and biological durability. It is thus crucial to understand moisture dynamics in wood products to optimise their usage. The movement of water through wood is complicated by the fact that the coarse capillary system is interconnected via smaller openings. For softwood, tracheids dominate water transport and inter-tracheid pits play an important role on water movement along radial and tangential directions [2,3]. Compared with softwood, hardwood has a more complex structure. Water conducting conduits in hardwood are composed of joined vessel elements end to end. Water transport in three dimensions, longitudinal, tangential and radial, of three different softwood species has been investigated by means of neutron radiography before [4]. Engineered wood materials, however, can have a different moisture dynamics behaviour, obviously still related to the properties of solid wood. Plywood is an important engineered wood material, which is manufactured by gluing solid wood veneers and pressing them together at high temperature. Its mechanical and physical properties are moisture dependent as well [5]. Although the water transport theory in solid wood has been well investigated [6], it has been rarely studied in plywood. A thorough understanding of water transport behaviour in plywood is valuable to optimise its production and application. The cross layered structure and presence of glue line between

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http://dx.doi.org/10.1016/j.conbuildmat.2014.09.095
0950-0618/

layers alters the water movement compared to solid wood. The main water movement directions of plywood are faces and side edges. Hence, it is interesting to investigate the water transport behaviour of plywood along these directions and compare it with related solid wood in dynamic water conditions.

To monitor the water distribution in wood products, several approaches have been used. The average moisture content (MC) of plywood exposed outdoors was continuously monitored by weighing [7]. To further continuously monitor the moisture distribution among layers of plywood, the electrical MC measurement method was introduced by Li et al. [8]. Other state-of-the-art techniques have also been used to monitor water movement in wood and wood-based products, e.g. magnetic resonance imaging, X-ray CT scanning and neutron imaging. Magnetic resonance imaging allows monitoring the free water movement in wood materials [9]. Research with X-ray CT scanning revealed the internal structure and density distribution of wood materials [10,11]. Compared with the above two approaches, neutron imaging is more suitable to determine moisture distribution due to the high attenuation of the neutron beam by hydrogen nuclei [12,13].

The objective of this paper is to investigate the water distribution in plywood and related solid wood during water uptake and air drying in climatized conditions. Several specimens of plywood and solid wood were prepared and scanned with X-ray CT in order to obtain a 3D view of their internal structure. Water uptake and air drying was then periodically monitored by neutron radiography. For solid wood, liquid water uptake in longitudinal, radial and tangential direction of three different hardwood species was monitored. For five different plywood panels glued with PF and UMF, liquid water uptake/air drying from the faces and the side edges was monitored and quantified. To better investigate the difference in moisture dynamics between plywood and solid wood, all plywood panels are uncoated. The relationship between water distribution and the microstructure of the specimens was analysed by combining the data from neutron radiography and X-ray CT scanning. The classical uptake/air drying test was performed on three replicates of the five plywood panels under study to evaluate the results obtained by neutron radiography and X-ray CT scanning.

2. Materials and methods

2.1. Preparation of the specimens

Solid wood specimens were prepared from three different hardwood species: poplar (*Populus* spp.), birch (*Betula* spp.) and okoumé (*Aucoumea klaineana Pierre*). For each species, three $25 \times 10 \times 10\ mm^3$ specimens were sawn in longitudinal, tangential and radial direction and 25 mm along the water uptake direction. Plywood panels were produced by European plywood companies. Two specimens from each plywood panels (Table 1), were cut to the size of $10 \times 30 \times$ panel thickness mm^3 and $10 \times 10 \times$ panel thickness mm^3 (Fig. 1) respectively. For laboratory water dynamics test, three replicates of each plywood panels measuring $50 \times 50 \times$ panel thickness mm^3 were prepared. All specimens were without knots, decay or any obvious defects. The four sides of each specimen, parallel to the water uptake direction, were sealed with a two component polyurethane sealant to ensure that water uptake was only possible in a single direction.

Plywood is manufactured by cross-gluing veneers together. The veneers are cut (peeled) perpendicular to the grain with the knife parallel to the grain [14]. As such, the water ingress direction of the veneers is longitudinal and tangential when water penetrates from a side edge of plywood. If water is absorbed from the face, the radial direction in veneer is the water ingress direction (Fig. 2).

2.2. Neutron radiography and experimental procedures

For this experiment, the Neutron Transmission Radiography (NEUTRA) beamline of the Paul Scherrer Institute (PSI) in Villigen, Switzerland was used. The same beam-line was utilised as described in Sedighi-Gilani et al. [4]. Fig. 3 shows an overview of the experimental setup, in which 4 specimens were mounted in a custom-made aluminium sample holder. The detector consisted of a scintillator CCD camera system and a field of view of $70.5 \times 70.5\ mm^2$ was applied in this experiment. The distance between specimens and detector needs to be as short as possible to minimise the effect of geometrical unsharpness [15]. Therefore the specimens were positioned in front of the detector at a distance of approximately 10 mm. The water container underneath the specimens was filled with demineralised water and positioned on a z-translation stage. The height of the water container could be adjusted by remotely controlling the height of this stage. The exposure time was 30 s per radiography with an approximate resolution of 68 μm/pixel.

Before uptake water, a neutron radiograph of the specimens was acquired. Next, the water container was lifted such that the bottom of the specimens was in contact with the water surface. Water uptake was monitored for a period of 20 min taking a radiograph every 40 s. The specimens were then removed from the beam line and uptake water continued in a similar setup in an acclimatised room for several hours. During these periods neutron radiographies were taken periodically. Plywood specimens were monitored after approximately 2, 3, 7 h of water uptake for the side edge experiment and after approximately 1.5, 4.5, 16.5, 25 h for the face water uptake. For solid wood, specimens were scanned after approximately 1, 3, 5.5, 10 h of water uptake. After water uptake, all specimens were removed from the water and air drying started. The plywood specimens were scanned after approximately 2, 5, 13.5 h of air drying for the side edge experiment and 1, 2, 3 h of air drying for the face experiment respectively.

2.3. X-ray scanning and image processing

Before water uptake, all specimens were scanned with HECTOR, the latest system developed by the Ghent University Centre for X-ray Tomography (www.ugct.ugent.be) in collaboration with X-ray Engineering (XRE bvba, Ghent, Belgium) [16]. The voxel pitch of the reconstructed grid is approximately 30 μm. To acquire further detailed data on the microstructure of a selection of specimens and explain some of the observed phenomena, the Nanowood CT scanner [17], also built at the Ghent University Centre for X-ray Tomography, was used to scan regions of interest of specimens during a second water uptake experiment, after the neutron experiments. The specimens were in contact with demineralised water in the same direction as in the neutron experiments. They were removed from the water after 0, 10, 20, 60 and 120 min and scanned. To avoid drying, the scan time was optimised to 8 min per specimen. Only the region close to water uptake face was scanned, with a resolution of approximately 20 μm. In order to obtain vessel size of solid wood specimens, the Nanowood CT scanner was also used to scan them with a resolution of approximately 7 μm. Reconstruction of all samples was performed using the construction software Octopus [18].

2.4. Water content quantification with neutron radiography

Neutron radiography is based on measuring the intensity of the neutron beam after transmittance through an object. Hence, water content could be calculated using the similar method described in Sedighi-Gilani et al. [4].

In this experiment, to calibrate and evaluate the accuracy of neutron radiography for measuring water thickness, an aluminium water step wedge was always positioned in the field of view during the experiment. The step wedge is composed of aluminium and contains five different water steps, i.e. 0.5 mm, 1 mm, 1.5 mm, 1.75 mm, and 2 mm (Fig. 4).

Table 1
Structure of the plywood panels.

Code	Wood species	Glue	# Of plies	Veneers (mm)	Thickness (mm)	Coating
P1	Poplar	UMF	7	1.3/2.6/2.6	14.9	No
P2	Poplar	PF	7	1.0/2.5/2.8	14.6	No
B1	Birch	PF	11	1.4/1.4/1.4	15.0	No
B2	Birch	PF	11	1.9/1.4/1.45	15.7	No
O1	Okoumé	PF	7	1.3/3.0/2.0	15.2	No

PF: phenol formaldehyde glue; UMF: urea melamine formaldehyde glue.
Veneer thickness: top veneer/inner cross/inner parallel.