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STUDY ON THE PENETRATION BEHAVIOUR OF WATER IN CORNER JOINTS BY MEANS OF NEUTRON RADIOGRAPHY

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ABSTRACT

Corner joints with different treatments and surface coatings were artificially weathered. After the weathering the samples showed conspicuous differences in the opening of the glued joints. On these samples the water uptake was ascertained at the Paul-Scherrer-Institute in Villigen (CH) by means of neutron radiography. The neutron radiographic investigation made it possible to retrace the water absorption by the samples and to make statements on the quantity of the absorbed water. Still it was not possible to make definite quantification due to dimensional instability which results of the swelling process during the water absorption. An outlook for further methodical improvements will be given in the conclusions.

KEY WORDS: wood connections, artificial weathering, neutron tomography, coating systems, water penetration

INTRODUCTION

Wood, which is exposed to changes in moisture content beneath its fibre saturation point, is subject of swelling and shrinking processes. The swelling respectively the shrinking process varies in great extent for the different cutting directions (longitudinal, radial, tangential). The maximum swelling in longitudinal direction accounts for ca. 0,6%, in radial direction 6% and in tangential direction 12%. The water adsorption (liquid water) is 6-15 times higher in longitudinal direction than perpendicular to the grain. This dissimilitude of the wood properties in the different cutting directions is called anisotropy (Kollmann 1951, Grammel 1989). Wooden joints that comprise wood with different cutting directions show after long-term exposure to an alternating atmosphere the formation of cracks and an opening of the glue joint. Good examples for this phenomenon are window frames. If the swelling process is constrained by an external force effect, as it is e.g. by the adhesives in wooden joints or in a wood connection with different fibre directions, the cellular tissue is consequently modified by the compression strain especially in direction perpendicular to the grain. This restrained swelling leads to permanent plastic deformations (Niemz 1993) which can lead to further formation of cracks within the wood structure. Via these openings in the connection (Fig. 1) further water can penetrate into the wood. The elevated level of wood moisture content offers ideal life conditions for wood-destroying micro-organisms namely fungi. To survive a vast majority of fungi needs free accessible water and air.

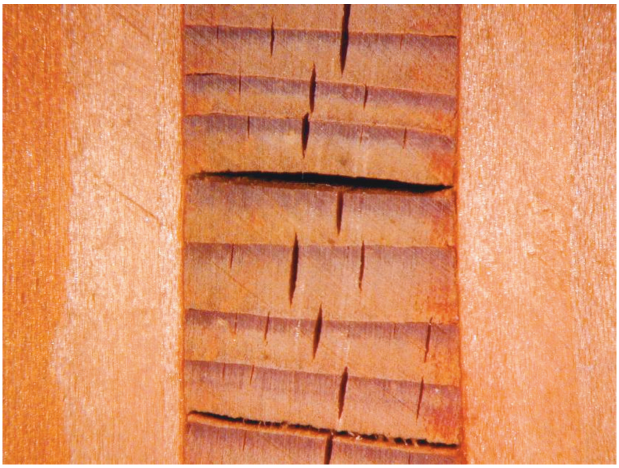

Fig. 1: Radial and tangential cracks within a sample due to restrained swelling (caused by different swelling in grain direction)

To avoid the opening of joints and cracks and by this the penetration of water and fungi wooden constructions are often treated with a variety of chemical wood preservatives. A new method for the non-destructive characterisation of wood is neutron radiography (Bucur 2003). Neutron radiography can be used to assess to which degree the different wood preservatives can prevent the penetration of water by anticipating the formation of cracks and joint openings. As Lehmann et al. (2001) respectively Niemz et al. (2004) showed, the utilisation of neutron radiography is particularly suitable for the investigations of wood. This is notably true for the determination of differences in the water content, because of the attenuation of the neutron beam by the hydrogen atoms. This fact can be harnessed to trace water movements as well in living plants (Nakanishi and Matsubayashi 1997, Nakanishi et al. 2002) as in wood as a building material (Niemz 2002). Thus the method of neutron radiography was used in this investigation to evaluate to which extent different wood preservatives and wood treatments affect the water absorption of wooden corner joints. The tests were carried out at the neutron transmission radiography facility (NEUTRA) which uses neutrons supplied by the Spallation neutron source (SINQ) at the Paul-Scherrer-Institute (PSI), Villigen, Switzerland (Bauer 2003, Lehmann and Pleinert 1998).

MATERIAL AND METHODS

Material

Corner joints made of spruce with different treatments and surface coatings were studied. The wooden elements had a mortise and tenon joint and were weathered for 6 weeks in an alternating atmosphere (humid/dry) (Fig. 2).

Fig. 2: Weathered specimen (untreated, no surface coating) with mortise and tenon joint; clearly visible is the opened joint between vertical and horizontal haunch

The corner joints had the following dimensions: leg length 200 mm, width 50 mm, thickness 30 mm. After the weathering the specimen's leg's lengths were shortened for the investigations to 85 mm. The corner joints varied in their treatment and surface coating. Table 1 gives an overview on the different treatments.

Tab. 1: Different treatments and surface coatings on the tested corner joints:

Case:	Surface coating/treatment:
1	- uncoated
2	- entire sample coated with Pento-Fluid after bonding
3	- the bond area was exclusively treated with Aidol end-grain protection
4	- similar treatment as treatment no. 3 with adjacent treatment with Pento-Fluid
5	- coating with standard window varnish
6	- surfaces (only face sides) coated with fibre glass laminate
7	- joints coated with Remmers V-joint-Protection

Methods - Experimental implementation
Weathering

The weathering of the specimens was realised in accordance with DIN 53384, mode B (total radiation 290 – 450 nm) in a Global UV Testing chamber 200 SB (Weiss Umwelttechnik GmbH). The following cycle was repeated 167x (1002 h) with continuous irradiation:

- 2 h sprinkling of the specimens at 20°C black standard temperature
- 6 h drying of the specimens at 60°C black standard temperature, 25% relative humidity

The joint opening of the connections was ascertained with an impinging light-optical microscope and an image processing software (Olympus DP).

Radiographic measurements
General physical principles

Neutrons are as well as protons part of the atomic core but bear unlike protons and electrons no electric charge. Due to their neutral electric behaviour neutrons can penetrate deep into test specimens, which makes them ideal for the investigation of inner structures and procedures.

Neutron radiography is based on the principles of transmission measurements. Collimators lead a neutron beam on a specimen. Behind the specimen a detector is placed which records the neutron beam weakened by the specimen. At which extend the neutron beam is weakened depends on the specimen's properties, like elementary composition and density. Namely hydrogen atoms have a rather high interaction probability with neutrons. This is why chemical compounds which comprehend hydrogen can be easily distinguished from materials with a different proportion of hydrogen. Thus the penetration behaviour of water (Niemz et al. 2002) and adhesives (Niemz et al. 2004) in wood could be described by means of neutron radiography. After passing the specimen the transmitted neutrons are registered as a two-dimensional distribution by the detector. As result grey scale images are obtained, which are used as base for the consequent analyses.

Implementation

Before testing the specimens were dried 24 h at 60°C. The dried specimens were placed on small bars in shallow aluminium basins, which are all but transparent for the neutron beam. The basins were filled with water so that the specimens were standing approximately 3 mm deep in the water. Two of the bowls each with two specimens were placed in the metering chamber.

In order to observe how the water penetrates into the corner joints neutron radiographic recordings were made in the following 24 hours. In the first hours a picture was taken every 2 minutes, later every 30 minutes. As detector a cooled, high sensitive CCD-Camera observing the light emission from a neutron sensitive scintillator was used. The field of view accounted for 223x223mm resp. 2048x2048 Pixel. Therefore the effective pixel size is in the order of 0.11 mm.

Interpretation of the images

As result of the neutron radiography pictures of grey tone grades were obtained (Fig. 3). In the raw data images the corner joints appear as black shapes, which is due to a high attenuation of the neutron beam resulting from the high content of hydrogen in wood as an organic material. In order to pursuit the water uptake the pictures had to be enhanced. These were subsequently standardised on the background (Fig. 4). To determine the quantity of the water absorbed in a certain period, the standardised pictures were divided by a standardised picture of the corner joints in dry condition (Fig. 5).

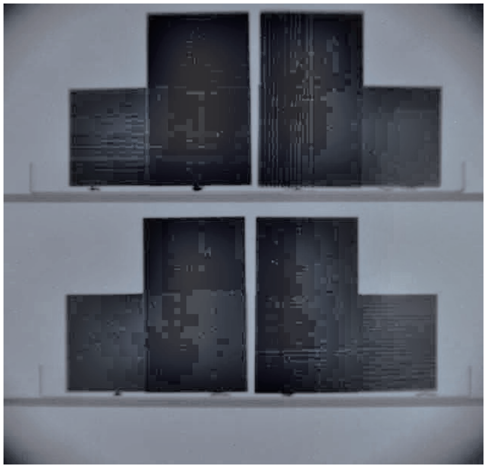

Fig. 3: Raw data image of the dry corner joints; the corner joints appear as black shapes due to the high attenuation of the neutron beam

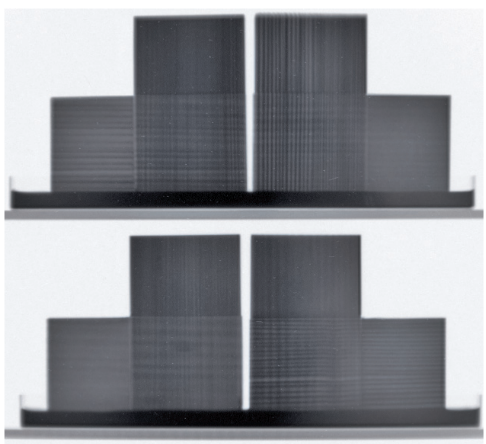

Fig. 4: Neutron radiographic picture from the beginning of the tests standardised on the background

The ascertainment of the absorbed water quantity was made by determining the alteration of grey tone grades between the standardised pictures. On this account profiles were laid in the picture in proximity to the waterline and thus the exact grey tone grade values could be determined (Fig. 6). With the obtained values the amount of absorbed water could be evaluated.

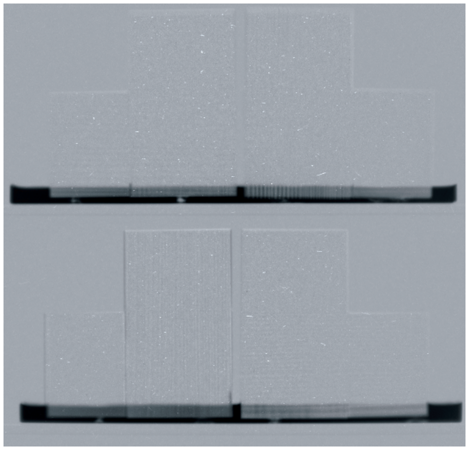

Fig. 5: Neutron radiographic picture from the beginning of the tests standardised on the background and the dry samples

Fig. 6: Standardised neutron radiographic picture 30 minutes after the start of the tests. For the ascertainment of the water absorbed a profile (white line) was laid in proximity of the water surface

In accordance with the attenuation law the intensity of the neutron beam behind the sample can be calculated as follows:

$$I = I_0 \cdot e^{-N \cdot \sigma \cdot d} \qquad (1)$$

I_0 = incident intensity of the neutron beam [grey levels]
I = weakened intensity of the neutron beam [grey levels]
N= nuclear density [cores/cm^3]
σ = interaction probability of the neutrons [cm^2]
d = sample thickness
L = Avogadro's constant

under consideration of

$$N = \frac{\rho^{H_2O}}{M} \cdot L \qquad \text{[Cores/cm}^3\text{]} \qquad (2)$$

$$I = I_0 \cdot e^{-\frac{\rho}{M} \cdot L \cdot \sigma \cdot d} \qquad (3)$$

after transforming this equation the density of the specimen can be obtained

$$\rho = -\ln\left(\frac{I}{I_0}\right) \cdot \frac{M}{L \cdot \sigma \cdot d} \qquad \text{[g/cm}^3\text{]} \qquad (4)$$

from that follows for dry and wet specimens

$$\rho_{1;2} = -\ln\left(\frac{I_{1;2}}{I_0}\right) \cdot \frac{M}{L \cdot \sigma \cdot d} \qquad \text{[g/cm}^3\text{]} \qquad (5)$$

I_1 = weakened intensity of the neutron beam of the dry specimen [psl = photostimulated luminescence in the detector]
I_2 = weakened intensity of the neutron beam of the wet specimen [psl]
ρ_1 = density of the dry specimen [g/cm^3]
ρ_2 = density of the wet specimen [g/cm^3]
M = atomic weight [g/mol]

The density of the absorbed water can be calculated as follows:

$$\rho_{H_2O} = \rho_1 - \rho_2 = -\left[\ln\left(\frac{I_2}{I_0}\right) - \ln\left(\frac{I_1}{I_0}\right)\right] \cdot \frac{M}{L \cdot \sigma \cdot d} \qquad \text{[g/cm3]} \qquad (6)$$

This term can be summarized:

$$\rho_{H_2O} = -\ln\left(\frac{I_2}{I_1}\right) \cdot \frac{M}{L \cdot \sigma \cdot d} \qquad \text{[g/cm}^3\text{]} \qquad (7)$$

The calculation of the absorbed water was accomplished with following physical values:

D =3cm   L = $6{,}022.10^{23}mol^{-1}$
M =18 g/mol   σ = $3{,}0.10^{-23}$ cm^2

RESULTS AND DISCUSSION

Qualitative evaluation of the joint openings

At the beginning of the experiments the splices of the corner joints were all closed. In the course of the tests an opening of the joints due to constrained swelling during the weathering could be ascertained. Table 2 gives an overview on the observed joint openings.

Tab. 2: Results of the joint openings after weathering

Case	Number of samples	Joint opening [mm]	Characterisation
1	2	0.05-1.93	conspicuous, ± consistent opening of the joints on all sides; extreme opening on one narrow face
2	2	0.02-0.63	conspicuous joint opening on the front sides, joints on narrow faces ± unimpaired
3	2	0.12-1.25	slight joint openings on the front faces, conspicuous openings on the narrow faces
4	2	0.09-1.46	erratic opening of the joints; most conspicuous on front faces
5	2	0.05-0.85	joints on narrow faces ± unimpaired; joints on front faces slightly opened
6	2	0.0-0.49	no joint opening on the front faces; joints on narrow faces slightly opened
7	2	0.12-0.85	slight joint openings on narrow faces; conspicuous opening on front faces

The openings of the joints were varying exceedingly between the different treatments and surface coatings. But not only the extent of the opening was varying but also the location of the apertures. Depending on the treatment respectively the surface coating the corner joints showed openings on their broad front faces or the narrow faces in the area between tenon and mortise.

Untreated corner joints

The untreated specimens showed differing tendencies in the opening of their joints. They differed from conspicuous and more or less consistent openings of all joints to extreme joint openings on side and scarcely any on the other. The openings varied from 0,05 mm to 1,93 mm on the narrow faces and from 0,05 mm to 1,06 mm on the front faces. The mean opening of the joints accounts on the front faces for 0,45 mm and 0,35 mm on the narrow faces.

Pento-Fluid

The specimens treated with Pento-Fluid after the bonding showed an opening of the glue joints only on the front faces. The narrow faces were virtually not opened. The joints on the narrow faces were opened from 0,02 mm to 0,52 mm with a mean opening of 0,18 mm. The openings on the front faces varied from 0,09 mm to 0,63 mm with a mean opening of 0,38 mm.

Aidol cross section preservative

The specimens treated with Aidol cross section preservative on the bond area showed a conspicuous opening of their joints on the broad front faces and extreme as well as consistent joint openings on their narrow faces. The openings on the narrow faces varied from 0,16 mm to 1,29 mm with a mean opening of 0,59 mm. On the front faces the openings ranged from 0,12 mm to 0,61 mm with a mean opening of 0,34 mm.

Combined treatment with Aidol end-grain protection and Pento-Fluid

These specimens showed an erratic opening of the joints on all sides. Some openings were more conspicuous than others but they were present on all sides of the specimens. On the narrow faces the joints opened 0,09 mm to 1,2 mm with a mean opening of 0,36 mm, while the joints on front faces had opened from 0,07 mm up to 1,46 mm with a mean opening of 0,51 mm.

Standard window varnish

The joints of these specimens were slightly to conspicuously open on their broad front faces but virtually unimpaired on their narrow faces. The joints on the narrow faces opened 0,05 mm to 0,56 mm with a mean opening of 0,25 mm. The joint openings on the broad front faces varied from 0,02 mm up to 0,85 mm with a mean opening of 0,33 mm.

Fibre glass laminate

The specimens with fibreglass laminate coating on their front faces showed only slight joint openings on the narrow faces on none on the coated front faces. The joints on the narrow faces showed openings up to 0,49 mm with a mean opening of 0,15 mm.

On the cross- sectional areas of the narrow faces a greater number of small fissures could be seen.

Remmers V-joint protection

The specimens whose joints were treated with the V-joint protection showed conspicuous and consistent openings on the front faces and slighter and more irregular joint openings on the narrow faces. On the front faces the joint openings ranged from 0,16 mm to 0,85 mm with a mean opening of 0,42 mm while the joint openings on the narrow faces varied from 0,12 mm to 0,71 mm with a mean opening of 0,36 mm.

Neutron radiography

After 12 h the investigated specimens had absorbed conspicuously different amounts of water (Fig. 7). The joint where the two wood pieces are linked as well as the different fibre orientation can be distinctively detected for all treatments. For the specimens whose joint did not open the increase in water absorption is mainly due to the varying fibre orientation of the two wood pieces from which the corner joints were made of. On the left side of the graph, where the fibres were oriented horizontally the water absorption is perspicuously lower than on the right side, were the fibre orientation was perpendicular to the water surface. The joint between the two linked wood pieces shows for the bigger part of the tested samples an important increase for the amount of absorbed water. This is mainly due to an opening of the glue joint in these specimens.

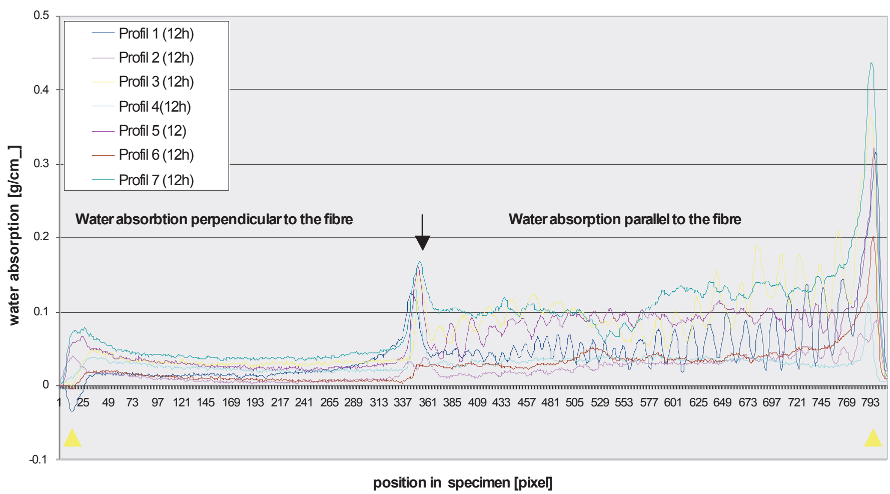

Fig. 7: Water absorption of after 12 hours for the different samples; the vertical joint is distinctively visible (black arrow); the fibre orientation is visible by the varying absorption on both sides of the joint (left: fibre orientation horizontal, right side: vertical);

Generally it could be ascertained that there is as expected an important relation between the opening of the glue joints and the amount of absorbed water (Fig. 8 and Fig. 9). The samples with little or no opening of the glue joint as the specimens treated with Pento-Fluid respectively coated with fibre-glass laminate had a water absorption which lay far beneath the level of the other treatments. For these variants no explicit peak could be determined for the joint linking the individual parts of the specimens. Such peak could be observed on the other hand for the entity of the other samples. Besides of the untreated specimens it is striking that some of the treatments show an even higher joint opening and by this a greater water absorption than the untreated samples.

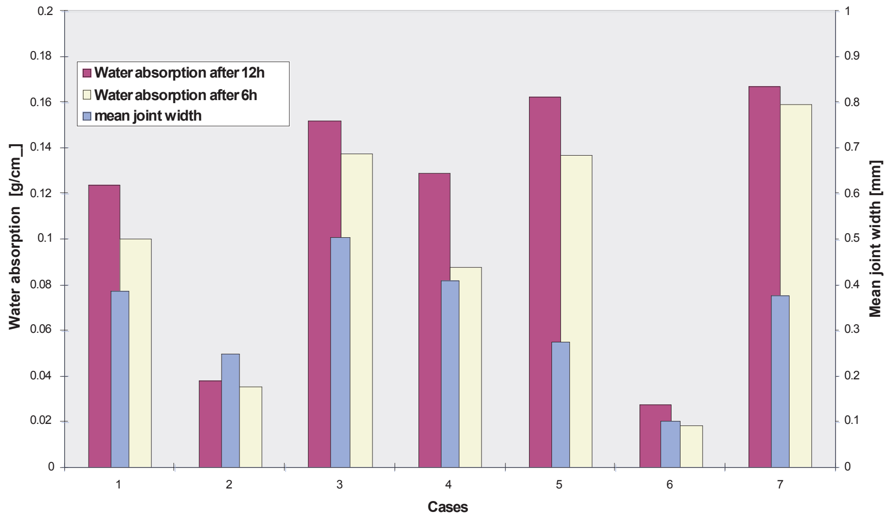

Fig. 8: Water absorption and mean joint opening on the specimens;

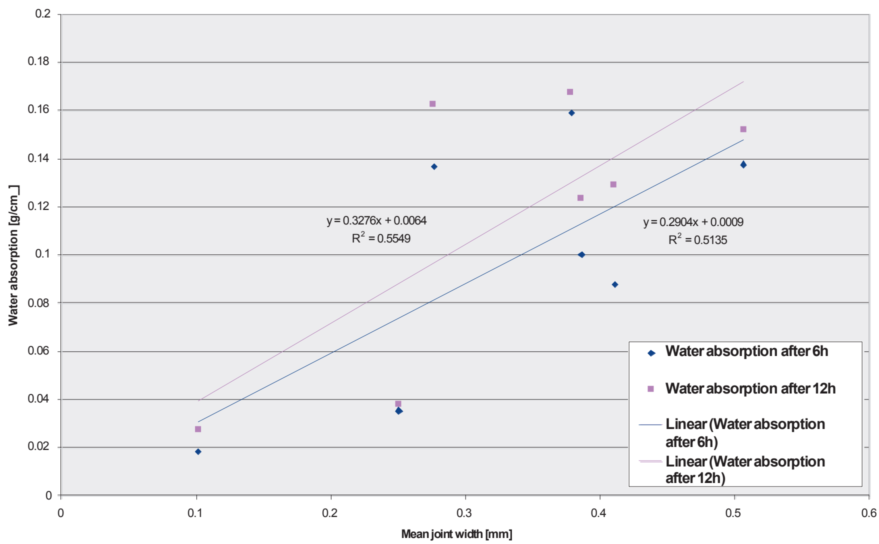

Fig. 9: Relation between mean joint opening and water absorption

Besides the attenuation by the amount of absorbed water the results of the neutron radiographic analyses were considerably influenced by the size changes due to the swelling of the samples induced by the alteration of wood moisture. This phenomenon is especially noticeable on the outer parts of the samples which can be seen in Fig. on the outermost left and right of the graph (yellow arrows). Consequently this leads to errors in the calculation of the exact quantity of absorbed water. To gain exact values the dimensional alterations have to be taken in account. This problem will be treated in current and future projects of this working group using x-rays to retrace the structural alterations due to swelling in shrinking.

CONCLUSIONS

It was shown that the moisture impact and the distribution of water inside the corner joints can be visualised and measured using neutron imaging methods. A further improvement of the investigations can be done by means of referencing with X-ray methods, where the wood matrix is imaged independently and the water can be investigated more sensitively.

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