In-plane mechanical properties of acetylated birch plywood and its response to humidity elevation

YUE WANG
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Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Licentiate of Engineering on Wednesday the 24th May 2023, at 10:00 a.m. in M108, Brinellvägen 23, Stockholm.
Abstract
Due to the recent flourish of modern timber structures, there is an increasing demand for engineered wood products (EWPs). However, outdoor exposure of EWPs often poses a risk of durability-related issues. For load-bearing timber structures, especially those in the outdoor environment, the combination of wood modification by acetylation and concept of EWPs allows manufacturing more durable and stable timber elements. This thesis concerns the angle-dependent in-plane mechanical properties of plywood manufactured from acetylated birch veneers (ABP). Specifically, tensile, compressive, shear and bending tests were conducted at three different load-to-face grain angles, namely from 0° (parallel), 22.5°, to 45°. The test results were compared with ordinary unmodified birch plywood (UBP) concerning stress-strain relationships, failure modes, strength, and elastic properties. Besides, for better understanding the moisture effect on the mechanical properties of both acetylated and unmodified birch plywood, specimens of both type were conditioned in climate chambers under three different environments, with the temperature of 20°C and elevating relative humidity (RH) from 35% to 65% to 95%. In this case, specimens with the load-to-face grain angles of 0°, 45°, and 90° were tested. The influence of both RH and measured moisture contents (MC) on bending strength and stiffness was evaluated. Variations of utilized brittleness terms under different RH conditions and load-face grain angles were also studied. Prediction formulas of mechanical properties with MC were derived by performing linear regressions among test results. The test results reveal that ABP possesses equivalent mechanical properties to UBP specimens. Under relative humidity elevation, acetylated plywood depicts more stable mechanical properties but higher brittleness than untreated specimens.

Keywords
Birch plywood; wood modification; acetylation; in-plane mechanical properties; load-to-face grain angle; moisture effect.
Sammanfattning

Marknaden för träbaserade byggsystem har expanderat kraftigt under senare år vilket inneburit ökad efterfrågan på förädlade träprodukter, så kallade engineered wood products (EWPs). Utomhusexponering av EWPs innebär dock ofta en risk för beständigshetsrelaterade problem. För bärande träkonstruktioner i utomhusmiljö möjliggör kombinationen av trämodifiering genom acetylering och EWP, en tillverkning av träkonstruktionselement med både hög beständighet och hållfasthet. Denna avhandling berör de mekaniska egenskaperna hos plywood tillverkad av acetylerade björkfaner. Specifikt utfördes drag-, tryck-, skjuvnings- och böjtester i förhållande till fibervinkeln hos plywoodens ytfaner vid 0° (parallellt med fiberriktningen), 22,5°, och 45°. Testresultaten jämfördes med kommersiell omodifierad björkplywoods egenskaper avseende spännings- och töjningsförhållanden, orsaker till brott, styrka och styvhet. Dessutom genomfördes liknande tester där prover konditionerats i tre olika klimat för att undersöka inverkan av klimatet på de mekaniska egenskaperna hos både acetylerad och omodifierad björkplywood. Konditioneringen genomfördes i klimatkammare vid en temperatur av 20°C vid 35, 65 respektive 95 % relativ luftfuktighet (RF). I detta fall belastades proverna i förhållande till fibervinkeln hos ytfanären vid 0°, 45° och 90°. Inverkan av konditioneringen i olika klimat studerades med avseende på böjhållfasthet, styvhet och sprödhet. Testresultaten visar att acetylerad björkplywood har likvärdiga mekaniska egenskaper som omodifiederad. Vid förhöjd RF har acetylerad björkplywood mer stabila mekaniska egenskaper jämfört med omodifiederad björkplywood. Acetylerad björkplywood är dock sprödare.

Nyckelord

Björkplywood; trämodifiering; acetylering; mekaniska egenskaper i planet; belastningsriktning; klimategenskaper.
Preface

The work presented in this licentiate thesis was carried out at the Division of Building Materials, Department of Civil and Architectural Engineering, KTH Royal Institute of Technology in Stockholm, Sweden. China Scholarship Council and Svenskt Trä are gratefully acknowledged for the financial support. The work has also been supported by Vinnova project 2017-02712 “Bärande utomhusträ” within the BioInnovation program as well as the Kamprad Family Foundation (reference number: 20200013) and from Produktion2030, a strategic innovation program supported by Vinnova (reference number: 2021-03681), Swedish Energy Agency and Formas.

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Finally, I would like to give my gratitude to my family and friends, for their endless support, especially during the pandemic period.

Stockholm, March 2023
Yue Wang
List of appended papers
This thesis is based upon the following scientific articles referred to in the text by their roman numbers:

Paper I

Paper II

In the appended papers, the first author planned and performed the majority of the experiments, analyzed the analytical and numerical models, wrote the manuscript with the help of the co-authors.
# Nomenclature

## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>COV</td>
<td>Coefficient of Variation</td>
<td></td>
</tr>
<tr>
<td>EWP</td>
<td>Engineered wood product</td>
<td></td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear variable differential transformer</td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>Moisture content</td>
<td></td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td></td>
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</tbody>
</table>

## Latin Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross-sectional area</td>
<td>m²</td>
</tr>
<tr>
<td>b</td>
<td>Width of birch plywood</td>
<td>m</td>
</tr>
<tr>
<td>h</td>
<td>Height of birch plywood</td>
<td>m</td>
</tr>
<tr>
<td>d</td>
<td>Depth of birch plywood</td>
<td>m</td>
</tr>
<tr>
<td>MOEₜ(𝑐)</td>
<td>Tensile or compressive elastic modulus</td>
<td>N m⁻²</td>
</tr>
<tr>
<td>fₘ</td>
<td>Edgewise bending strength</td>
<td>N m⁻²</td>
</tr>
<tr>
<td>fₜ(𝑐)</td>
<td>Tensile or compressive strength</td>
<td>N m⁻²</td>
</tr>
<tr>
<td>Fᵣₘₜₙₜ</td>
<td>The failure load</td>
<td>N</td>
</tr>
<tr>
<td>Fᵣₜ</td>
<td>Resultant force in the tensile zone</td>
<td>N</td>
</tr>
<tr>
<td>ΔF</td>
<td>Load increment</td>
<td>N</td>
</tr>
<tr>
<td>G_destroyed</td>
<td>Shear modulus from destructive tests</td>
<td>N m⁻²</td>
</tr>
<tr>
<td>G_modified</td>
<td>Modified shear modulus</td>
<td>N m⁻²</td>
</tr>
<tr>
<td>I</td>
<td>Second moment of area</td>
<td>m⁴</td>
</tr>
<tr>
<td>k</td>
<td>Shear correction coefficient</td>
<td>1</td>
</tr>
<tr>
<td>l₁</td>
<td>Original length of strain gauge</td>
<td>m</td>
</tr>
<tr>
<td>lᵣ</td>
<td>Reduced length</td>
<td>m</td>
</tr>
<tr>
<td>L</td>
<td>Span of birch plywood</td>
<td>m</td>
</tr>
<tr>
<td>MOE_b</td>
<td>Elastic bending modulus</td>
<td>N m⁻²</td>
</tr>
<tr>
<td>t</td>
<td>Thickness of birch plywood</td>
<td>m</td>
</tr>
<tr>
<td>t₁</td>
<td>Thickness of inner veneer</td>
<td>m</td>
</tr>
<tr>
<td>t₂</td>
<td>Thickness of face veneer</td>
<td>m</td>
</tr>
<tr>
<td>Δu</td>
<td>Deformation increment</td>
<td>m</td>
</tr>
<tr>
<td>Δuₜ</td>
<td>Bending deformation increment</td>
<td>m</td>
</tr>
<tr>
<td>Δu_LVDT</td>
<td>LVDT deformation increment</td>
<td>m</td>
</tr>
<tr>
<td>Δuₛ</td>
<td>Shear deformation increment</td>
<td>m</td>
</tr>
<tr>
<td>W</td>
<td>Elastic section modulus</td>
<td>m³</td>
</tr>
</tbody>
</table>
### Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>Shear strain</td>
<td></td>
</tr>
<tr>
<td>γ\text{correction}</td>
<td>Correction factor</td>
<td></td>
</tr>
<tr>
<td>ε\text{t(c)}</td>
<td>Tensile or compressive strain</td>
<td></td>
</tr>
<tr>
<td>ε\text{tu}</td>
<td>Tensile strain at failure</td>
<td></td>
</tr>
<tr>
<td>θ</td>
<td>Face grain angle to the loading or beam axis</td>
<td>°</td>
</tr>
<tr>
<td>τ</td>
<td>Shear stress</td>
<td>N m^{-2}</td>
</tr>
</tbody>
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1. Introduction

1.1. Birch plywood and its structural applications

Birch timber, a rather short-lived pioneer hardwood species widespread in the Northern Hemisphere, is suitable for construction purposes in terms of strength and stiffness. As one of the earliest produced engineered wood products (EWPs), plywood consists of an uneven number of thin veneers (also called plies), normally with a thickness from less than one millimeter to several millimeters, bonded together with an adhesive and with the grain direction of adjacent veneers perpendicular to one another [1]. The combination of superior mechanical performance of birch compared to softwood species and plywood with the cross-lamination configuration makes birch plywood promising for structural use.

During the last few decades, plywood depicts its imprint as connections in timber structures such as truss connections, beam-to-column connections, and portal frames [2–6]. Plywood gusset plates used in structural connections are competitive due to their renewability, modest environmental impact, high tolerance during assembly, good fire resistance, and relatively low cost compared to similar connections made of steel [7]. More recently, birch plywood has been studied regarding its mechanical properties and the possible utilization in innovative timber connections [8–10]. See Figure 1 for the illustration of some plywood applications in timber connections [11].
1.2. Acetylated wood and derived engineered wood products

Despite its versatile utility and superior strength, the application of birch plywood in outdoor environment is not recommended due to its poor durability (durability class 5 according to EN 350-1:2016 [12]). Wood-degrading fungi, humidity, and UV light essentially impair the technical properties of plywood by weakening the bonded veneers, which in turn weakens mechanical strength. The moisture penetration into veneer layers causes swelling, delamination, and characteristic waves on the plywood surface. Therefore, when using plywood in outdoor environments where regular wetting is possible, it is recommended not only to cover it from the outside with hydrophobic laminates, but also to treat the single veneers constituting the entire plywood board [13].
Acetylation, a wood modification method that involves a reaction between wood and acetic anhydride, has been studied extensively and has shown to be one of the most promising methods for the improvement of the technical properties and durability of wood products [14]. This process principally results in the esterification of the accessible hydroxyl (OH) groups in the wood cell walls, forming acetic acid as a by-product [14]. The working principle can be pictured as bulking the wood substance through blocking the wood polymers’ water-sensitive (hygroscopic) parts, i.e., replacing the OH-groups with water-resistant acetyl groups, so that the equilibrium moisture content (EMC) of the modified wood is reduced. Compared to unmodified wood, acetylated wood has shown considerably reduced hygroscopicity and improved dimensional stability [15–18]. Figure 2 illustrates the main working principle of the acetylation process.

![Figure 2. Illustration of acetylation process.](image)

Since it is relatively easy to realize a homogeneous impregnation on birch [13,19], plywood boards made of acetylated birch veneers, hereinafter referred to as acetylated birch plywood (ABP), should in principle be easy to manufacture and suitable for outdoor environments. Potential disadvantages related to acetylation is that the process usually leads to a) increased brittleness of the material and b) formation of cracks along the grain direction [20]. However, the cross-wise lay-up of veneers of plywood virtually eliminate the above-mentioned issues.

To summarize, plywood boards consisting of acetylated birch veneers are viable alternatives for structural sheets made from conventional building materials such as steel and aluminum. In addition, due to a so-called carbon sink effect [21], prolonging the service life of wood-based products results in a positive effect to mitigate greenhouse gas emissions by storing biomass carbon for longer periods.
Before using acetylated wood in load-bearing structures, the effect of acetylation on mechanical properties has to be investigated. In general, the impact of acetylation on lumber’s mechanical properties is found to be highly species-dependent. Hill [15] compiles several different reports on the modulus of rupture (MOR) and the modulus of elasticity (MOE); the results show an increase of 7% in both MOR and MOE for spruce. Bongers and Beckers [22,23] studied the MOE, MOR, shear strength, and compression strength on a pilot plant scale, and found that the mechanical properties of most species were increased by acetylation, especially with Scots pine and poplar. On the other hand, MOE and MOR of Radiata pine were decreased by the process. Larsson and Simonson [24] found that acetylation induced a reduction in MOE for pine sapwood in the order of 17%, along with reductions in MOR of approximately 5%. Virtually no change in mechanical properties could be determined for acetylated beech [25–27]. As for the influence of acetylation on birch, the limited number of strength tests that have been made to date shows that dry acetylated wood has practically the same tensile and bending strength properties as the untreated birch [16,17], but this conclusion is not consistent with altering acetyl contents from 16% to 22%.

There is also research relevant to acetylated EWPs, such as particleboards made from acetylated aspen flakes, which showed improved dimensional stability and biological resistance compared with similar untreated EWPs. Even though the mechanical properties of dry specimens were found to be somewhat reduced due to the acetylation process, since the reduction was not significant, the author concluded that mechanical properties should improve once a better wood-adhesive bonding is developed [18,28]. Hung et al. [29] assessed the effect of wood acetylation on mechanical properties and extended creep behavior of wood/recycled-polypropylene composites (WRPCs) and found excellent reinforcing effects.
1.3. Moisture influence on mechanical properties

The knowledge of the moisture influence on the mechanical properties of unmodified and acetylated birch plywood needs to be enhanced for a better design of outdoor structural birch plywood elements. Due to the pronounced in-plane anisotropy of plywood, particular attention should also be given to the variation of strength when plywood is loaded at different angles to the face grain. This study have importance for structural design since plywood material standards typically assess material strengths only parallel and perpendicular to the face grain based on ambient humidity [20].

The literature also reported that acetylation causes an increased brittleness in certain wood species [20,30]. The most common indexes adopted to quantify the brittleness of treated wood in the literature are based on fracture mechanics terms, e.g., critical stress intensity factors, fracture energy, etc. However, Matsumoto and Nairn [31] addressed that the fracture characterization of wood-based composite materials requires continuous monitoring of toughness as a function of crack growth via albeit non-standard fracture tests. Consequently, these fracture tests are usually highly effort demanding and require adequate hardware, software, and measurements with high precision.

Therefore, a relatively effort-saving and robust index is needed to quantify the brittleness of untreated and modified wood. Even preferably, it can be based on the results of static strength tests so that the moisture influence on the brittleness can also be depicted.

1.4. Aim and objectives

The first objective of this thesis concerns the angle-dependent in-plane mechanical properties of plywood made of acetylated birch veneers (ABP). Specifically, tensile, compressive, shear and bending tests were conducted at three different load-to-face grain angles, namely 0° (parallel), 22.5° and 45°.
The second objective is to compare the mechanical properties of acetylated birch plywood (ABP) with ordinary unmodified birch plywood (UBP) concerning stress-strain relationships, failure modes, strength, and elastic properties.

The third objective is to study the influence of moisture contents (MC) variations on the bending strength and stiffness of UBP and ABP specimens. Specimens of both types were conditioned in climate chambers under three different environments, with a temperature of 20°C and elevating relative humidity (RH) from 35% to 65% to 95%. Specimens with load-to-face grain angles of 0°, 45°, and 90° were tested. The influence of both RH and MC on bending strength and stiffness were evaluated. Prediction formulas of mechanical properties with moisture contents were then derived by performing linear regressions of test results.

Moreover, two brittleness terms in the literature are adopted to investigate the moisture effect on the brittleness of both unmodified and acetylated birch plywood specimens, the detailed definition of terms will be illustrated later in Section 2.3.1.2.
2. Materials and methods

2.1. Materials

The studied unmodified birch plywood (UBP) panels are commercial products from Koskisen Oy (Järvelä, Finland). Each plywood panel consisted of 15 veneers with the nominal thickness of 21 mm. The inner 13 veneers had an identical thickness of 1.4-1.5 mm while the face veneers were thinner. Phenol formaldehyde resin was used as adhesive between each veneer. Further information of detailed veneer layups can be found in the literature [8,9].

The studied acetylated birch plywood (ABP) panels were so-called pilot products. Birch lumber was first rotary-cut into veneers with a thickness of around 1.5 mm. Then the birch veneers were acetylated by ACCSYS (Arnhem, The Netherlands). According to their industrial methods, the veneers were acetylated to sufficiently high acetyl content, i.e. approximately 20-22%. This process applies a vacuum-pressure impregnation of liquid anhydride, followed by heating (gas) and the removal of the acetylated veneers with the by-product acetic acid. The treatment temperature is around 130-150°C, and the treatment time varies from 16 to 24 hours per wood dimension [20,32]. After the treatment was completed, the acetylated birch veneers were sent back to the plywood manufacturer. Finally, by hot-pressing and gluing the veneers orthogonally with PRF adhesive, plywood boards with a total thickness of around 22.5 mm (15 veneers) were produced. Hereinafter, plywood made of acetylated birch veneers is referred to as acetylated birch plywood, abbreviated as ABP, and the unmodified birch plywood is abbreviated as UBP. Figure 3 illustrates the manufacturing process of the ABP boards.
2.2. In-plane mechanical properties

2.2.1. Experiments

Specimens with three different loading force-to-face grain angles, i.e., 0°, 22.5°, 45° were tested in tension, compression, panel shear, and edgewise bending. Waterjet cutting was applied to prepare see specimens, see arrangement and geometrical details of all relevant ABP specimens are illustrated in Figure 4. Please refer to [9] for the cutting arrangement of the UBP specimens.
The specimens were conditioned in the climate chamber Binder MKFT 240 under the controlled temperature of 20°C and the relative humidity (RH) of 65%, which was tested via weight control. The moisture content (MC) was measured on samples with similar mass to the tested specimens using the oven-dry method described in EN 322 [33]. The measured average density of the ABP and UBP specimens were respectively 730 and 693 kg/m³, and the MC obtained from the oven-dry method were respectively 5.6% and 11.9%.

All the tests were performed on a universal testing machine MTS 810 with a capacity of 100 kN. The test setup and the configuration of specimens were adapted from the testing standard ASTM D3500 [34] for tensile tests, ASTM D3501 [35] for compressive tests and EN 789 [36], ASTM D1037 [37], ASTM D2719 [38] for the shear tests.

For the tension, compression and shear tests, two 38 mm-long extensometers were installed for measuring the elastic properties. For the bending test, the elastic modulus was derived based on the force and mid-span deflection interval, which was measured using the attached strip and two LVDTs. See Figure 5 for the test setup and the information about the specimens.
More details regarding the specimen geometry and test procedure have been introduced in Paper I [9].

2.2.2. Evaluation of strength and stiffness

2.2.2.1. Tension and compression

The tensile strength $f_t$ of the test piece is defined as the maximum force recorded in loading history divided by the cross-sectional area $A$ at the specimen’s mid-height. The tensile elastic modulus is calculated as the slope of the linear portion of the stress-strain curve, as illustrated in Eq. (1).
where $MOE_t$ is the tensile elastic modulus; $\Delta \sigma_t$ is the stress increment between 15% to 35% of the failure stress; $\Delta \epsilon_t$ is the strain increment corresponding to $\Delta \sigma_t$.

The compressive strength $f_c$ and the compressive elastic modulus $MOE_c$ are defined in a similar way as for the tensile strength and the tensile elastic modulus.

2.2.2.2. Panel shear

The investigated shear property in this study concerns the panel shear (or edgewise shear). The shear modulus is calculated from the shear strain measured by two extensometers. However, due to the apparatus geometry, the shear strain within the area of the attached strain gauges is not uniformly distributed along the width direction, but be concentrated around the vicinity of the central line. Therefore, the combination of extensometers with the designed geometry would underestimate the shear strain, thereby overestimating the shear modulus. Consequently, to compensate for the aforementioned effects, several non-destructive tests were performed on homogeneous birch plywood specimens without slits, so as to derive the correction factor for the shear modulus. The detailed derivation steps of the correction factors are given in Paper I [9].

The shear strength $f_s$ is defined as the maximum force over the cross-sectional area. The corrected shear modulus is calculated as in Eq. (2).

$$G_{modified} = \gamma_{correction} \cdot \frac{\Delta \tau}{\Delta \gamma}$$

where $\Delta \tau$ is the shear stress increment between 15% to 35% of the failure stress; $\Delta \gamma$ is the shear strain increment measured from the strain gauges corresponding to $\Delta \tau$; $\gamma_{correction}$ is a geometrical correction factor on measured shear modulus, derived by comparing the results from destructive and non-destructive tests.
2.2.2.3. Edgewise bending

The investigated bending property in this study concerns the in-plane bending (or edgewise bending). By assuming a linear-elastic bending stress distribution at the failed cross-section, the bending strength is calculated as follows:

\[ f_m = \frac{M}{W} = \frac{3 \cdot P_{\text{max}} \cdot L_s}{2 \cdot b \cdot h^2} \]  
(3)

where \( P_{\text{max}} \) is the failure load; \( L_s \) is the beam span; \( b \) is the width of cross-section; \( h \) is the height of cross-section.

The bending stiffness \( MOE_m \) is calculated based on the slope within the linear portion of the load-deformation curve considering Timoshenko beam theory, where the bending deflection equals the measured deflection subtract the contribution from shear, as given in Eq. (4).

\[ MOE_m = \frac{\Delta P \cdot L_s^3}{4 \cdot b \cdot h^3 \cdot (\Delta d - \frac{\Delta P \cdot L_s}{4 \cdot K_s \cdot G \cdot b \cdot h})} \]  
(4)

where \( MOE_m \) is the bending elastic modulus; \( \Delta P \) is the force increment between 15% to 35% of the failure load; \( \Delta d \) is the measured mid-span deflection increment corresponding to \( \Delta P \); \( K_s \) is the shear correction coefficient, a common value for orthotropic beam \( K_s = \frac{5}{6} \) is used in this study; \( G \) is the panel shear modulus measured in Section 2.2.2.2.

2.3. Edgewise bending properties’ response to humidity elevation

2.3.1. Experiments

The influence of acetylation, face grain angle and elevation of relative humidity, on the edgewise bending properties were also investigated in this thesis.

It is worth mentioning that the panel thickness in this test series are different compared with the ones mentioned earlier in Section 2.1. Specifically, the unmodified birch plywood investigated herein was a 21 veneer commercial plywood product, with a nominal thickness of 30 mm.
And the acetylated birch plywood had the same number of veneers and the total thickness of 31.5 mm. The veneer layup is illustrated in Figure 6a below.

Both ABP and UBP specimens were conditioned in climate rooms with three different environments (Env1: 20°C 35% relative humidity (RH); Env2: 20°C 65% RH; Env3: 20°C 95% RH). Specimens with load-to-face grain angles of 0, 45, and 90 degrees were selected. Each test series consisted of around 10 replicates. The density of birch plywood pieces was calculated by dividing each part's weight by its respective nominal volume. The moisture content was determined on tested specimens using the oven-dry method, as described in EN 322 [33].

After the conditioning, specimens were tested following the three-point bending test scheme. The testing standard EN 13879 describes the edgewise bending testing method for wood-based panels [39]. It also suggested that the test of small size specimens should be in accordance with EN 310, where 3-point bending test is elaborated [40].

In this paper, the span-to-height ratio was kept constant as 16. Therefore, in the adopted edgewise bending test, the beam depth $d$ and beam span $L$ were respectively 20 mm and 320 mm, the beam width $b$ equals to the panel thickness, which was 30 mm for UBP specimens and 31.5 mm for ABP specimens. The specimen dimension is demonstrated in Figure 6b.

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Figure 6. a) Veneer layup of untreated and acetylated birch plywood specimens, b) dimensions of a test specimen.
A similar three-points bending test setup with the one shown in Figure 5d was adopted in this study as well. Paper I presents more detailed loading procedures [9].

2.3.1.1. Strength and stiffness
The investigated bending property in this test series also concerns the in-plane bending (or edgewise bending). By assuming a linear-elastic bending stress distribution at the failed cross-section, the bending strength and stiffness were evaluated in the same way as mentioned earlier in Section 2.2.2.3.

2.3.1.2. Brittleness terms
As mentioned earlier, a relatively effort-saving and robust index is needed to quantify the brittleness of untreated and modified wood. Even preferably, it can be based on the results of static strength tests so that the moisture influence on the brittleness can also be depicted. In this study, two brittleness terms were adopted to give an intuitive comparison on the brittleness of different specimen groups.

Phuong et al. [41] heat-treated Styrax tonkinensis wood under different environments and later conducted static bending tests on all specimens. They calculated the ratio (%) of the work absorbed in the elastic region to the total work absorbed to maximum load, used this ratio as a brittleness index to evaluate the brittleness of heat-treated wood, and found that the brittleness increased significantly after heat treatment. Under the most severe heat treatment conditions, brittleness could be increased by as much as four times that of the original brittleness. The brittleness index they proposed is hereinafter referred to as BI, and its definition is illustrated in Figure 7a.
Chen et al. [42] performed flexural tests on bamboo and proposed a similar factor based on the elastic bending stress-strain curves, to which they referred as the ductility factor (DF). Flexural ductility was evaluated by the ductility factor (DF), which measures the capacity of a material to withstand plastic deformation before it breaks. A similar concern was addressed in several design standards for timber structures. The brittleness factor (BF) they proposed is illustrated in Figure 7b. The reciprocal of the proposed ductility factor was converted into so-called brittleness factors in this study and hereinafter referred to as BF.

Both the brittleness indexes (BI) and brittleness factors (BF) were adopted to analyze the influence of moisture on the ductility of unmodified and acetylated specimens.
3. Results and discussion

3.1. In-plane mechanical properties

3.1.1. Experimental results

Figure 8 depicts all the stress-strain curves for each type of test and loading angle until the maximum stress has been reached. The red-colored curves represent the acetylated ABP specimens with the typical curves (the ones with the least deviation from the mean curves) highlighted. For UBP specimens, only the typical curves are presented as in blue-color [9].

Figure 8: Stress-strain relationships of birch plywood specimens in (a) tension, (b) compression, (c) shear and (d) bending tests.
As illustrated in Figure 8, typically, the tensile test curves are virtually linear elastic until failure. The specimens tested under compression, shear, and bending, on the other hand, showed a certain degree of elasto-plasticity after the initial elastic range. The mean values, coefficient of variation, and characteristic values are summarized in Table 1.

To give a nominal comparison on mechanical properties of ABP due to angle dependence, the angular factor $k$ is proposed and it is defined as:

$$k_{strength} = \frac{Strength_{\theta, mean}}{Strength_{0, mean}}$$

(3)

$$k_{stiffness} = \frac{Stiffness_{\theta, mean}}{Stiffness_{0, mean}}$$

(4)

where $Strength/Stiffness_{\theta, mean}$ is the mean value of strength/stiffness from tension, compression, shear, bending test at an angle; $Strength/ Stiffness_{0, mean}$ is the strength/stiffness for this type of test when loaded parallel to the grain ($0^\circ$).

The angular factor $k$ of tensile, compressive, shear and bending strength and stiffness, at different load-to-face grain angles, are also presented in Table 1.
It can be seen in Figure 8 and Table 1 that the tensile, compressive, and bending behavior of acetylated birch plywood showed a significant dependence on the loading angles, with the specimens loaded parallel to the face-grain possessing both the highest strength and elastic modulus, while the ones loaded at 45° to the face grain yield the lowest.

Specifically, when being loaded in tension, compression and bending, the stiffness when loaded at 45° to the face grain was only around 21-27% of that parallel to the face grain (0°). This variability is less dramatic for strength, with reduction factors of 27%, 53% and 41% for tensile, compressive and bending strength respectively.

Quite the opposite trend was found for the shear properties, where the specimens loaded at 45° exhibited the highest shear strength and stiffness, and the ones loaded parallel to the face grain exhibited the lowest. The ratios of shear strength/stiffness along the weakest axis (0°) and the strongest axis (45°) were 0.29 and 0.21 respectively.
3.1.2. A comparison with unmodified birch plywood

Paper I, i.e. Wang et al. [9], reported the in-plane mechanical properties of unmodified UBP. In light of that, a comparison between ABP and UBP specimens was conducted, as shown in Figure 9.

![Graphs showing tensile/compressive/shear/bending strength and stiffness of acetylated and unmodified birch plywood (ABP and UBP), in relation to the load-to-face grain angle.]

Figure 9. Tensile/compressive/shear/bending strength and stiffness of acetylated and unmodified birch plywood (ABP and UBP), in relation to the load-to-face grain angle.
The comparison in terms of tensile properties shows that when the force direction is parallel to the face veneer grain direction (0°), the ABP specimens had similar strength and stiffness as the UBP. When the load angle shifts to 22.5° and 45°, the ABP specimens possessed similar stiffness but slightly lower tensile strength compared with the UBP specimens.

As for the performance in compression, the ABP and UBP specimens had similar compressive elastic modulus. However, ABP had higher compressive strength compared with UBP at all investigated loading angles, especially at 0°.

When comparing the shear test performance, the ABP specimens possessed both higher shear strength and shear modulus than UBP specimens. This discrepancy was less noticeable when the force was parallel to the face grain, and was more pronounced when the load-to-face grain angle was at 45°.

Further comparing the bending strength and stiffness, in all three examined groups of load-to-face grain angles, except for the slightly higher strength and stiffness at 0°, the acetylated groups showed no significant difference in comparison with the unmodified groups.

Table 2 indicates the relative difference in mechanical properties of ABP specimens with reference to UBP specimens, positive effects are marked as red-colored fonts.

Table 2. Relative difference ratios between the strength (left column) and the stiffness (right column) of ABP and UBP. The properties of UBP are taken as the reference.
Beckers et al. [23] suggested that increased mechanical properties brought by the acetylation process can be explained by the increase of mechanical properties with decreasing moisture content [43,44]. They also suggested that the decrease of mechanical properties by acetylation can be explained by the fact that acetylation process involves heat treatment (hydro-thermal effects) under acetic conditions, which causes degradation of cellulose, hemi-cellulose and lignin, resulting in a reduction on mechanical properties [43–45].

### 3.2. Edgewise bending properties’ response to humidity elevation

#### 3.2.1. Strength, stiffness and brittleness terms

The piston load-deflection at mid-span curves of all six groups of tests series under all three condition environments, are presented in Figure 10. Red and blue color respectively represent the acetylated and unmodified birch plywood specimens. The solid line, dashed line and the dotted line respectively present the test results obtained under 35%, 65% and 95% relative humidity environments. Only the typical curves (the ones with the least deviation from the mean curves) are presented for a better visibility.

![Figure 10. Load-deflection curves of acetylated and unmodified birch plywood specimens tested under three point bending. The specimens are conditioned under three humidity environments, at different load-to-face grain angles.](image)

As can be observed in Figure 10, at all three load-face grain angles, the acetylated specimens usually give stronger and stiffer response than the
unmodified specimens, except for 45° specimens under 35% and 65% RH, the strength of some ABP specimens were slightly lower than that of unmodified specimens. With the increase of relative humidity in the atmosphere from 35% to 65% to 95%, namely, with the line type transition from solid to dash to dotted lines in Figure 10, the UBP specimens (blue lines) encountered a much more significant strength reduction than the ABP specimens. This reduction seems to be not as significant as the reduction in stiffness.

Adopting the terms definition given in Equation 2&3, the average bending strength, stiffness are summarized in Table 3.

Table 3. Bending strength and stiffness of acetylated and unmodified specimens at three load-face grain angles, under three condition atmospheres. The numbers within the parentheses indicate the standard deviation.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>RH</th>
<th>Bending strength (MPa)</th>
<th></th>
<th>MOEₘ (GPa)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0°</td>
<td>45°</td>
<td>90°</td>
<td>0°</td>
</tr>
<tr>
<td>ABP</td>
<td>35%</td>
<td>93.3 (4.0)</td>
<td>34.9 (1.9)</td>
<td>86.3 (4.0)</td>
<td>11.9 (0.6)</td>
</tr>
<tr>
<td></td>
<td>65%</td>
<td>86.5 (2.7)</td>
<td>34.4 (1.7)</td>
<td>80.1 (2.0)</td>
<td>10.9 (0.7)</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>77.1 (4.7)</td>
<td>32.8 (1.4)</td>
<td>72.2 (3.3)</td>
<td>10.4 (0.9)</td>
</tr>
<tr>
<td>UBP</td>
<td>35%</td>
<td>74.5 (2.0)</td>
<td>35.4 (1.1)</td>
<td>73.3 (1.5)</td>
<td>9.8 (0.4)</td>
</tr>
<tr>
<td></td>
<td>65%</td>
<td>69.9 (2.0)</td>
<td>33.3 (1.5)</td>
<td>66.4 (2.6)</td>
<td>9.3 (0.4)</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>42.9 (2.8)</td>
<td>24.8 (1.8)</td>
<td>40.3 (2.5)</td>
<td>8.4 (0.9)</td>
</tr>
</tbody>
</table>

As mentioned earlier in Section 2.3.1.2, to give an effort-saving and robust index to quantify and compare the brittleness of untreated and acetylated wood and their variation with moisture, the aforementioned energy-derived brittleness indexes (BI) and elastic strain-derived brittleness factors (BF) were calculated based on the test curves and summarized in Table 4.
Table 4. Brittleness index (BI) and brittleness factor (BF) of ABP and UBP specimens at three different load-face grain angles and relative humidity levels. The numbers within the parentheses indicate the standard deviation.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>RH</th>
<th>Britteness index (BI)</th>
<th>Brittleness factor (BF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0°</td>
<td>45°</td>
</tr>
<tr>
<td>ABP</td>
<td>35%</td>
<td>0.53 (0.07)</td>
<td>0.49 (0.06)</td>
</tr>
<tr>
<td></td>
<td>65%</td>
<td>0.42 (0.04)</td>
<td>0.45 (0.06)</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>0.41 (0.02)</td>
<td>0.39 (0.05)</td>
</tr>
<tr>
<td>UBP</td>
<td>35%</td>
<td>0.45 (0.06)</td>
<td>0.31 (0.04)</td>
</tr>
<tr>
<td></td>
<td>65%</td>
<td>0.39 (0.04)</td>
<td>0.30 (0.01)</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>0.15 (0.04)</td>
<td>0.20 (0.03)</td>
</tr>
</tbody>
</table>

Summarizing the test data given in Table 3 and Table 4, the variation of the edgewise bending strength, stiffness, BI (brittleness index) and BF (brittleness factor) of both UBP and ABP specimens under three relative humidity levels and moisture contents, are presented below in Figure 11. The solid, dashed, and dotted line types respectively stand for specimens with load-to-face grain angles at 0, 45, and 90 degrees.
Figure 11. Variation of edgewise bending strength, stiffness, brittleness index, and brittleness factor, of ABP and UBP specimens versus three relative humidity levels and moisture contents.
One observation in Figure 11a-b is that for a certain line type, the red curves are usually above the blue ones. This indicates that in all condition atmospheres with three RH levels, the acetylated specimens usually possess higher bending strength and stiffness. When increasing the RH from 65% to 95%, the strength of acetylated specimens encountered a reduction of around 10% while the unmodified specimens were weakened by nearly 40% from 69.9 MPa to 42.9 MPa. No significant difference was observed in terms of bending stiffness reduction. Proceed to Figure 11c-d, on the other hand, the higher brittleness indexes and brittleness factors indicate that the ABP specimens are usually more brittle under the same RH level. With the increase of relative humidity, both BI and BF of UBP and ABP specimens decreased, which reflects a decreased brittleness therefore an increased ductility, this observation was more significant in unmodified specimens.

Besides, the variation of mechanical properties can also be plotted versus the measured moisture contents, as shown in Figure 11e-h. With the increase of moisture content, an almost linear trend in the reduction of bending strength and stiffness values was depicted for both acetylated and untreated specimens. It is also noticeable that the better moisture resistance of acetylated specimens is usually discussed in the context of under the same environment, namely, in the same atmosphere where the temperature and relative humidity is the same. However, this disparity is less significant if one evaluates the properties of ABP and UBP specimens under the same moisture content. This phenomenon reflects the working principle of the acetylation process. Compared to unmodified specimens, most of the mechanical properties enhancement for acetylated specimens is due to reduced moisture content levels when being conditioned in the same atmosphere.

The literature has reported that acetylated specimens possess better moisture resistance [46,47]. Combing all eight subfigures in Figure 11, this better moisture resistance of acetylated specimens can be interpreted from two perspectives. First, under the same temperature and relative humidity levels, the bending stiffness and strength of the ABP specimens were
usually higher than for the UBP specimens. Second, with the increase of relative humidity in the atmosphere, the decline of mechanical properties, especially bending strength, was also less significant in the ABP than for the UBP specimens.

Despite the influence on mechanical properties brought by acetylation on timber, the literature also addressed that acetylation would cause an increased brittleness in certain wood species [20,48,49]. This concern is illustrated by calculating the energy-derived brittleness index (BI) and strain-based brittleness factor (BF). As in Figure 11c, d, g, h, both indexes give similar trend on the influence of moisture contents on the brittleness of specimens. When the moisture increase, both the brittleness index and factor decreased, which indicates a reduced brittleness, i.e., an increased ductility. This increased ductility with moisture increase is favorable in terms of structural design, since a more ductile material will increase the structures’ static ductility, allow force/stress redistribution, allow energy dissipation, and increase structural robustness of the building [50–52]. However, this beneficial increase in ductility brought by moisture increases is contradicted by the moisture resistance ability. As a result, the ductility increase is more noticeable for the UBP compared with the ABP specimens.

3.2.2. Correlation between mechanical and moisture contents

In order to derive a generalized correlation between mechanical properties and moisture content values at different load-face grain angles. Linear regressions were performed in Matlab R2019b [53] by inputting the moisture content as independent variables, and the mean test values of bending strength and stiffness as dependent variables. The corresponding fitted equations and R-square values are presented in Table 5.
Table 5. The fitted equations of bending strength and stiffness with corresponding moisture content values and R-square values.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Angle</th>
<th>Bending strength (MPa)</th>
<th>Bending stiffness (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fitted equation</td>
<td>$R^2$</td>
</tr>
<tr>
<td>ABP</td>
<td>0°</td>
<td>$-2.19 \times MC + 100.40$</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>$-0.30 \times MC + 36.08$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>$-2.02 \times MC + 93.61$</td>
<td>0.96</td>
</tr>
<tr>
<td>UBP</td>
<td>0°</td>
<td>$-2.42 \times MC + 95.32$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>$-0.80 \times MC + 42.00$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>$-2.48 \times MC + 93.66$</td>
<td>0.99</td>
</tr>
</tbody>
</table>

The error bars of test values are plotted versus the fitted equations as a comparison in Figure 12. The error bars represent the standard deviation.

As presented in Figure 12, linear regressions give a satisfactory correlation between moisture content variation and mechanical properties within the studied hygroscopic range.
3.2.3. Nominal comparison under different service classes

Moreover, for a comparison between properties with different magnitudes, the bending stiffness and strength values of acetylated and untreated birch plywood specimens were converted into nominal values. The mechanical properties measured for specimens conditioned under Env2 (20°C 65% RH) were taken as the reference when deriving the nominal values. At a certain load-face grain angle, by dividing the test values at different humidity environments by the test values under Env2 (20°C 65% RH), the nominal values are defined as:

\[ k_{\text{nominal}} = \frac{MOE(f)_{m,\theta,\text{RH}}}{MOE(f)_{m,\theta,65\%}} \]  

while \( \theta = 0^\circ, 45^\circ, 90^\circ \) and \( \text{RH} = 35\%, 65\%, 95\% \).

The nominal values of bending stiffness and strength of acetylated and unmodified specimens at three different load-face grain angles under different RH levels are presented in Table 6.

Table 6. Nominal values of MOE and bending strength of ABP and UBP specimens at three different load-face grain angles and relative humidity levels.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>RH</th>
<th>Bending strength (MPa)</th>
<th>MOE(_m) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0°</td>
<td>45°</td>
</tr>
<tr>
<td>ABP</td>
<td>35%</td>
<td>1.08</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>65%</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>0.89</td>
<td>0.95</td>
</tr>
<tr>
<td>UBP</td>
<td>35%</td>
<td>1.07</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>65%</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>0.61</td>
<td>0.74</td>
</tr>
</tbody>
</table>

An observation drawn from Table 6 is that, with RH increase, the mechanical property reduction is more significant in unmodified than in acetylated specimens, as well as more severe in strength than in stiffness. Under the same RH increment interval, the reduction is more significant at high relative humidity levels.
Specifically, when increasing the RH from 35% to 65%, the bending strength and stiffness of both the ABP and UBP specimens showed a reduction of up to ca 10%. Increase the RH further from 65% to 95%, the bending strength and stiffness of the ABP once again encountered a reduction by ca 10%. However, the mechanical weakening for unmodified specimens was much more significant at this relative humidity interval. At both parallel and the perpendicular to the face grain directions, the bending strength of UBP was reduced by over 40%. This strength reduction was less severe at 45° but still around 25%. The bending stiffness reduction of UBP specimens was around 10% at parallel and perpendicular to the grain direction, and around 25% for the sample with 45° face grain orientation.

Considering the angle-dependency, for both the UBP and ABP samples, the reduction of bending strength at higher RH levels was more significant for 0° and 90°, than for 45°. However, the exact opposite trend was observed in the bending stiffness reduction, namely, the stiffness reduction at higher RH levels was most pronounced for 45° specimens.

Eurocode 5 considered different service classes for assigning timber strength values in different load situations and relevant environmental conditions [54]. The service class classifications are defined as follows:

- Service class 1 (SC1) is characterized by a moisture content in the materials corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 65% for a few weeks per year (average moisture content in most softwoods will not exceed 12%).

- Service class 2 (SC2) is characterized by a moisture content in the materials corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 85% for a few weeks per year (average moisture content in most softwoods will not exceed 20%).

- Service class 3 (SC3) is characterized by climatic conditions leading to higher moisture contents than in service class 2.
In this study, the measured moisture contents for unmodified specimens under three conditioning environments were 8.4%, 10.8%, and 21.6%, respectively. Accordingly, the first (Env1: 20°C 35% RH) and second humidity environment (Env2: 20°C 65% RH) are classified as service class 1, and the third environment (Env3: 20°C 95% RH) is classified as service class 3. Therefore, the nominal ratio of mechanical properties conditioned under 95% RH over that under 65% RH, is classified as the SC3/SC1 values for the bending properties of ABP and UBP specimens, as indicated by the bold italic values in Table 6.

EN 1995-1-1 considers the factor $k_{mod}$ to modify strength values for various load-duration and service classes [54]. For plywood, depending on different load-duration classes, the ratio of service class 3 $k_{mod}$ value to service class 1 $k_{mod}$ value ranges from 0.78 to 0.83. This is simply a consequence of rounding errors, with the intended SC3/SC1 ratio being 0.8, as reported by Bongers et al. [55].

In Table 6, for acetylated specimens, the SC3/SC1 ratios for both the bend strength and stiffness were over 0.89 at all three angles. This reflects the conservatism of Eurocode 5. For unmodified specimens, on the other hand, the SC3/SC1 ratio for bending strength varied from 0.61 to 0.74, and that for bending stiffness varied from 0.75 to 0.92. This suggests that when accounting for the mechanical properties reduction of unmodified birch plywood specimens due to moisture, lower SC3/SC1 bending strength factors than the recommended values (0.8) in the Eurocode 5 were observed at all three angles. As for the stiffness reduction of unmodified specimens, the recommended SC3/SC1 factor by Eurocode 5 is conservative on bending stiffness at 0° and 90° but non-conservative at 45°.

As summarized by Bongers et al. [55], the above-mentioned disparity between the observed and the values recommended by EN 1995-1-1 is because the latter only gives a single set of $k_{mod}$ values for all stress types. This may have been a pragmatic decision by the code authors, putting ease of use over accuracy for this design aspect, in view of the fact that the majority of structural usage of wood-based materials is in service classes 1 or 2. Such pragmatism might be applicable for solid timber. However,
the case of plywood, as presented in this study, a more accurate conversion from service class 1 values to service class 3 values is suggested for both unmodified and acetylated specimens, preferably also taking angle dependency into account.
4. Conclusions and future work

This thesis first reveals the in-plane mechanical properties of acetylated birch plywood (ABP). The experimental result shows that all investigated tension, compression, shear and bending strength and stiffness depend strongly on the load-to-face grain angle. The specimens loaded parallel to the face-grain (0°) showed the highest tensile, compressive, and bending strength and stiffness properties, while the ones loaded at 45° to the face grain showed the lowest. For shear properties, quite the opposite trend was found, where the specimens loaded at 45° to the face grain showed the highest shear strength and stiffness, and the ones loaded parallel-to-the-face grain showed the lowest.

A comparison with unmodified birch plywood (UBP) was also made regarding strength, stiffness and failure modes. The ABP showed similar tensile strength and stiffness when being loaded parallel to the face veneer grain. When the loading angle shifted to 22.5° and 45°, the ABP specimens possessed similar stiffness but slightly lower tensile strength. When being loaded in compression, the ABP specimens had similar compressive elastic modulus, but higher compressive strength at all three investigated load angles. The shear properties of the ABP specimens possessed both higher strength and stiffness than the unmodified ones. This difference was less noticeable for loading parallel to the face grain, and was most pronounced for the load-face grain angle of 45°. Regarding the bending performance, the acetylated and unmodified groups showed no significant difference, except for a slightly higher strength and stiffness for acetylated ones at 0°.

Moreover, the effect of moisture on the edgewise bending properties of acetylated and unmodified birch plywood were also investigated and compared. Specimens with three different load-face grain orientations were manufactured from unmodified and acetylated plywood panels. They were conditioned in three different environments at 20°C with elevating
relative humidity (RH) levels from 35% to 65% to 95% RH. Subsequently, they were tested under three-point bending.

The edgewise bending strength and stiffness decreased with increasing RH for both the ABP and the UBP. When conditioned in the same RH, the bending stiffness and strength of the ABP was higher than that of the UBP. In addition, with increasing RH, the decline of the mechanical properties, especially the bending strength, was also less significant for the ABP than that for the UBP. This better moisture resistance of the ABP was particularly noticeable at high humidity levels. Considering the angle-dependency, for both UBP and ABP, the reduction of bending strength with elevating relative humidity, was more significant at 0° and 90° than at 45°. Quite the opposite trend was observed in bending stiffness reduction, i.e., the stiffness reduction when increasing the RH levels was most significant at 45°.

Both an energy-based brittleness index (BI) and an elastic strain-based brittleness factor (BF) were calculated to give an intuitive brittleness comparison between the ABP and the UBP specimens. It was found that under the same RH level, the ABP was, in general, more brittle than the UBP. With increasing RH, both the BI and the BF decreased, demonstrating a more ductile performance with higher relative humidity. This is beneficial in terms of structural design. However, since the mechanical properties of acetylated specimens are less prone to moisture variation, this ductility benefit from moisture increase is also less pronounced for ABP specimens.

Certain limitations of this thesis should also be addressed. Firstly, more specialized test series within the context of fracture mechanics should be performed to derive certain externally valid terms. As a suggestion, fracture energy, critical stress intensity factors, critical energy release rate, etc., should be measured and compared with other materials or serve as the input values for more refined numerical models. In addition, the conditioning at 95% RH in this study is more appropriately defined as a moist condition. Therefore, future test series are suggested to also involve water-saturated specimens to represent more severe wet conditions.
Future works are also planned to pursue the target of utilizing birch plywood as joint plates in truss corners. Firstly, this involves determining the fastener-bearing strength of birch plywood. Therefore, embedment test series of smooth dowels and screws into birch plywood is planned. After that, structural joints consisting of birch plywood plates and mechanical fasteners, loaded either in uniaxial tension or bending moment, are planned to be constructed and tested. Finally, future studies should also comprise development of analytical design methods validated via the aforementioned experimental results.
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