ORIGINAL ARTICLE

The durability of acetylated beech (*Fagus sylvatica* L.) laminated veneer lumber (LVL) against wood-destroying basidiomycetes

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Abstract

The overall aim of this study was to investigate the durability of acetylated beech (*Fagus sylvatica* L.) laminated veneer lumber (LVL) against wood-destroying basidiomycetes. The secondary objective was to test whether the specimen size affects the mass loss and durability assessment of wood-material under test. The durability test was based on the pre-standard prEN 113-3. Six materials (acetylated beech LVL, untreated beech LVL, beech solid wood, pine sapwood (*Pinus sylvestris* L.), larch (*Larix decidua* Mill.) 3-layer slab, larch solid wood) were tested using three specimen geometry designs ($50 \times 25 \times 15$ mm^3 as well as $50 \times 50 \times 19$ mm^3 with and without sealed edges) against *Coniophora puteana*, *Rhodonia placenta*, *Gloeophyllum trabeum*, *Trametes versicolor*, and *Pleurotus ostreatus*. The durability assessment was made using the arithmetic mean and median percentage mass loss (ML), the relative ML (*x*-values), and the decay susceptibility index (DSI). It was found that mass loss was affected by the test fungus, the material, and the specimen size and design, with the latter being the most essential factor in this study. In addition, the assessment parameter had a significant effect on the durability classification. Furthermore, small differences in ML resulted in different durability classes (DC) in some cases, whereas large differences in ML did not. However, acetylated beech LVL was always considerably durable (DC 1) against all tested fungi independent of the specimen design and durability assessment method.

1 Introduction

Acetylation of wood with acetic anhydride has attracted much attention in recent years by improving the durability and dimensional stability of wood. During acetylation of wood, hydroxyl groups react with acetic anhydride to form covalent bonds and acetic acid as by-product (Hill 2006). Acetylation is one of the few chemical wood modification methods that have established on the European market. Thereby, pine (*Pinus radiata* D. Don) was the primary wood

species (Bongers et al. 2013). Yet other wood species are also appealing for this process.

For instance, European beech (*Fagus sylvatica* L.) is one of the most important hardwood species in Europe and particularly prevalent in Germany and France. The mechanical properties of beech wood are significantly higher compared to other coniferous timbers such as Norway spruce (*Picea abies* Karst.), which are commonly used in the building trade (Wagenführ 2007), and may allow new designs in timber construction. However, the durability of beech against wood destroying fungi and its dimensional stability in contact with moisture are severely limited (Bicke 2019; EN 350 2016). Moreover, the false heartwood of beech is hard to impregnate (EN 350 2016). To overcome these limitations, acetylated veneer-based products such as laminated veneer lumber (LVL) and plywood are currently under development (Slabohm et al. 2022a; Wang et al. 2021, 2022).

In general, veneers are first acetylated and then bonded to veneer-based products. The bonding of acetylated wood has been the subject of extensive studies (Bongers et al. 2016; Frihart et al. 2017; Olaniran et al. 2021; Slabohm et al. 2022a, b; Slabohm and Militz 2022a; Treu et al. 2020; Vick and Rowell 1990). Additionally, numerous studies on

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materials made from acetylated veneer were conducted. For example, it was found that the mechanical properties of birch plywood are barely affected by acetylation (Wang et al. 2022). Another study discovered that acetylation does not prevent beech plywood from fire (Mohebby et al. 2007). Reduced wood-moisture interaction and improved dimensional stability were found for acetylated beech LVL compared to untreated references after submersion in water, but especially after a boiling-drying-boiling cycle (Slabohm and Militz 2022a). Following long-term outdoor exposure, acetylation does not significantly enhance the photostability of wood (Chao et al. 2020; Dunningham et al. 1992; Evans et al. 2000).

However, during the manufacturing of plywood and LVL, the material is exposed to temperatures of up to 150 °C, to cure the adhesive, and it is still unknown whether the bonded acetyl groups are cleaved-off (de-acetylate) in the presence of adhesives, high temperatures, and pressure. As a result of de-acetylation, the biological durability of the material could be reduced.

Imamura and Nishimoto (1986) tested the durability of acetylated LVL made of several softwood species against subterranean termites. Even after hot-bonding at 110 °C, they discovered improved durability. However, their research was limited to the durability against termite attack with a mode of action that can be significantly different from that against decay fungi. In another research, acetylated veneer-faced low-density particleboards were produced at temperatures of 160 °C for 5 min and tested in an 8-week soil block test (Rowell et al. 1989). The boards were resistant to *Tyromyces palustris* and *Trametes versicolor*. Nevertheless, acetylated veneer-faced low-density particleboards and acetylated beech LVL differ in a number of ways (for instance, resin type, pressing time, wood species, and the acetylation process). Another indicator that deacetylation did not occur is that the dimensional stability remained improved after hot-bonding (Slabohm and Militz 2022a, b) and was similar to that of acetylated solid wood (Rowell 2014). However, further research on the durability of acetylated veneer-based products is needed.

The durability of wood against white and brown rot fungi is often tested in laboratories using basidiomycete monocultures under most favorable conditions for fungal decay. Thereby, the oven-dry mass of sterilized specimens is determined before and after incubation with selected test fungi. However, worldwide durability standards vary with respect to specimen size and shape as well as incubation periods.

In Europe, EN 350 (2016) is the overarching standard that defines durability classes (DC) and refers to various test standards, such as agar plate tests according to EN 113-2 (2021). The latter is the preferred test method for determining the durability of solid wood. Test specimens of 50 (long.) $\times 25 \times 15$ mm^3 are incubated for 16 weeks to selected brown and white rot fungi. The mass loss (ML) caused by fungal decay is thereafter used to assign DCs. In contrast, the standard ENV 12038 (2002) describes a laboratory method for testing the durability of wood composites using specimens of $50 \times 50 \times$ thickness (mm^3). While the specimens are significantly larger compared to those required by EN 113-2 (2021), the incubation time is 16 weeks in both cases. Instead of DCs, ENV 12038 (2002) suggests to determine the decay susceptibility index (DSI). Low values indicate high resistance to fungal degradation, while high values indicate low resistance. For instance, DSI = 100% means that the sample was completely susceptible to fungal attack (Amusant et al. 2009).

In 2021, ENV 12038 (2002) was replaced by EN 113-3 (2021). The test procedure including specimen size and incubation time has been inherited, but the new standard allows for durability classification of wood composites. The latter is based on the median ML in coincidence with EN 113-2 (2021). It might be questioned whether the use of specimens of approximately the double volume will show the same ML and thus the same DC. Previous studies with solid larch heartwood (Brischke et al. 2021) showed that the wood specimens' format (shape and size) has a significant impact on both, the ML and the durability assessment. In addition, the effect of the large cut side edges of the specimens on ML during incubation has been debated. LVL, plywood and further composites are usually applied as large-sized boards with relatively small percentage of side edges, which ideally are sealed in outdoor applications. To mimic the real-life proportions of panel composites, the edges of small clear specimens might be sealed with a material that is impermeable for water and fungal hyphae.

The superior aim of this study was to determine the biological durability of acetylated beech LVL. The secondary objective was to test whether the specimen design possesses impacts on the ML of the specimens and the resulting durability assessment. Therefore, in total six different wood-based materials underwent comparative incubation experiments using different specimen designs.

2 Materials and methods

2.1 Materials

LVL made from acetylated beech was the material of interest and untreated beech LVL was used as a reference. Beech veneers (2200×1000 mm^2) with and without sections of discolored red-heart were used for acetylation at an industrial production plant of Accsys Technologies S.A. (Arnhem, The Netherlands), while half of the veneers remained untreated. The veneers were acetylated to a weight percent gain (WPG) of about 24.4% (SD = 0.5%) (Slabohm et al. 2022b).

Eight-layered LVL boards were bonded in a hydraulic press (HP-S 1200, Gottfried Joos Maschinenfabrik GmbH & Co. KG) at 150 °C for 30 min at a pressure of 1 N/mm². Prior to that, a hand roller was used to apply 180 g/m² of a 2-component phenol–resorcinol–formaldehyde (PRF) resin one-sided on seven veneers. The liquid hardener Prefere 5839 (Dynea AS) was mixed with Prefere 4040 resin (Dynea AS) at a weight ratio of 20:100 to create the PRF resin. After cooling, the surfaces were sanded (P100).

In addition, specimens were made from solid wood and 3-layer slabs, both made from European larch (*Larix decidua* Mill.) and used as additional reference materials and for benchmarking. A commercial larch 3-layer slab with a thickness of 19 mm was used. The surfaces were also sanded (P100). European beech and Scots pine sapwood (*Pinus sylvestris* L.) were used for manufacturing virulence control specimens.

2.2 Specimen preparation

Specimens of three different designs were prepared (Fig. 1). All specimens were oven-dried at 103 ± 2 °C, weighed to the nearest 0.01 g, leached according to EN 84 (2020), oven-dried, and weighed again. The mass loss during leaching (Δm_L) was calculated using the following Eq. (1):

$$\Delta m_L = (m_0 - m_{0L})/m_0 \times 100 \, [\%] \tag{1}$$

where Δm_L = mass loss during leaching [%], m_0 = oven-dry mass before leaching [g], m_{0L} = oven-dry mass after leaching [g].

After leaching, specimens were conditioned at 20 °C/65% RH. Half of the specimens of $50 \times 50 \times 19$ (long. × rad. × tang.) mm³ were sealed around all edges with polyurethane (Sikaflex® 221i, Sika Austria GmbH, Austria). The mass of the specimens was taken before and after the sealing was applied. The mass of the sealant was calculated using the following Eq. (2).

$$m_{sealant} = m_{unsealed} - m_{sealed} \, [g] \tag{2}$$

where $m_{sealant}$ = mass of the sealant [g], $m_{unsealed}$ = specimen mass before sealing [g], m_{sealed} = specimen mass after sealing [g].

2.3 Durability tests with basidiomycete monocultures

In total, 1080 specimens were exposed to basidiomycete monocultures. Twelve replicate specimens were used per combination of fungus, specimen design, and test material. All specimens were kept in a culture vessel (polyethylene jars) containing malt agar (4%). In each culture vessel, one specimen of $50 \times 50 \times 20$ mm² or two specimens of $50 \times 25 \times 15$ mm² were placed on stainless-steel washers. Prior to incubation, a 20-min pressureless steam sterilization was performed, followed by 24 h of cooling and another 10 min of steaming. A possible deacetylation could also occur during steam sterilization. A total of 72 specimens ($n = 6$ per material and specimen design) were stored on malt agar at 20 °C/65% RH and used for mass correction. As virulence control, Scots pine sapwood and European beech were used. The specimens were incubated for 16 weeks with the following test fungi:

- *Coniophora puteana* (Schumach.) P. Karst. (Eberswalde 15),
- *Rhodonia placenta* (Fr.) Niemelä, K.H. Larsson & Schigel (FPRL 280),
- *Gloeophyllum trabeum* (Pers.:Fr.) Murrill (Eberswalde 109),
- *Trametes versicolor* (L.) Lloyd. F. (CTB 863a),
- *Pleurotus ostreatus* (Jacquin ex Fries) Kummer (FPRL 40C).

After harvesting, the specimens were cleaned from adhering mycelium, weighed, oven-dried at 103 ± 2 °C, and weighed again. The mass loss due to fungal decay (ML) and
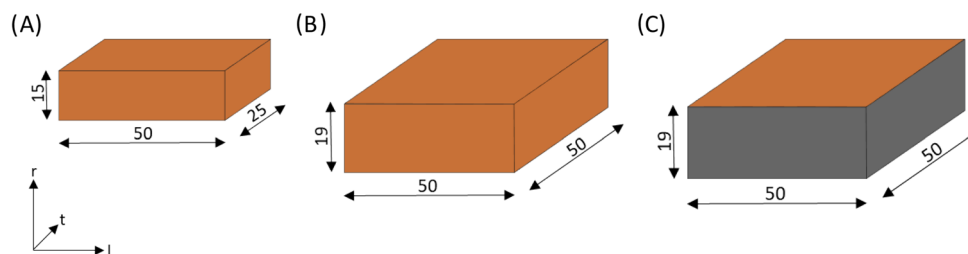

Fig. 1 Overview specimen designs. **A** Specimen according to EN 113-2 (2021), volume: 18.75 cm³; total surface: 47.5 cm², surface/volume ratio: 2.53 cm⁻¹; **B** specimen according to EN 113-3 (2021), volume: 47.5 cm³, total surface: 88.0 cm², surface/volume ratio: 1.85 cm⁻¹; **C** specimen according to EN 113-3 (2021), volume: 47.5 cm³, total surface: 50.0 cm², surface/volume ratio: 1.05 cm⁻¹. Anatomical directions for veneer-based products: *l* longitudinal, *r* radial, *t* tangential; the annual rings on solid wood specimens are rotated by 45°

the material moisture content (MC) were calculated using Eqs. (3) and (4).

$$ML\ (\%) = (m_0 - m_{i,0})/m_{i,0} \times 100 \tag{3}$$

$$MC\ (\%) = (m_i - m_{i,0})\ m_{i,0} \times 100 \tag{4}$$

where m_0 = the initial oven-dry mass before incubation [g], m_i = the wet mass after incubation [g], $m_{i,0}$ = the oven-dry mass after incubation [g].

2.4 Durability assessment

For each group, the arithmetic mean and median ML were calculated. In addition, x-values were computed using Eq. (5):

$$x = ML_{med,\ specimen}/ML_{med,\ reference} \tag{5}$$

where $ML_{med,\ test}$ = the median mass loss after incubation [%], $ML_{med,\ reference}$ = the median mass loss after incubation of Scots pine sapwood to *C. puteana*, *G. trabeum*, *R. placenta* and beech wood to *T. versicolor* and *P. ostreatus* [%].

The decay susceptibility index (DSI) was computed using Eq. (6).

$$DSI = T \times 100/S \tag{6}$$

where T = mass loss of an individual specimen [%], S = arithmetic mean percentage mass loss of the mass control specimens for each fungus (Scots pine sapwood for *C. puteana*, *G. trabeum*, *R. placenta* and beech wood for *T. versicolor* and *P. ostreatus*) [%].

Thereafter, DC were assigned to the groups according to Table 1.

2.5 Statistics

The statistical computing and graphics were made using the software R (RStudio Team 2022).

Boxplots were used to illustrate the distribution of the data set. The median is between the lower (where 25% of the data is less than this value) and upper (where 25% of the data is higher than this value) quartiles of the dataset.

The minimum and maximum value are shown by the two outermost lines, while the outliners are represented by dots.

The linear correlation was assessed using the Pearson correlation coefficient (r). Positive correlation is between 0 and 1, 0 indicates no correlation, and between 0 and −1 is a negative correlation.

3 Results and discussion

3.1 Test validity

The fungi *C. puteana*, *G. trabeum*, and *R. placenta* caused a mass loss (ML) of more than 20% on the virulence control specimens of Scots pine sapwood as well as *T. versicolor* and *P. ostreatus* on beech solid wood (as required in EN 113-3 2021). Moreover, the median ML of beech solid wood exposed to *C. puteana* exceeded 30% as required for at least one test fungus.

3.2 Durability of acetylated beech LVL

Acetylated beech LVL proved to be very durable (DC 1), no matter to which fungi it was exposed nor which specimen design and durability assessment was applied (Fig. 2 and Table 2). This coincides with findings from previous studies with acetylated solid wood from various species (Bollmus 2015; Brelid and Simonson 1999; Fodor et al. 2022; Hill et al. 2009; Mantanis et al. 2020; Militz 1991; Rowell 2016; Temiz et al. 2006). In contrast, some others reported that acetylated wood degradation is only inhibited (Alfredsen et al. 2016; Hill et al. 2005). For instance, after 28 weeks of exposure to *R. placenta*, acetylated Radiata pine (*Pinus radiata*) showed significant ML under optimum relative humidity and temperature conditions (Beck et al. 2018). In contrast, field tests have shown that acetylated wood and wood products can last for many years, even in soil contact without signs of decay (Brelid et al. 2000; Fodor et al. 2022; Mantanis et al. 2020).

The enhanced biological durability of acetylated wood has been explained by the following potential modes of protective action: (1) wooden cell wall polymers are not recognized by fungal enzymes, (2) nutrients, such as hemicelluloses, are not easily accessible because they are

Table 1 Durability classes (DC) of wood and wood composites exposed to basidiomycete fungi based on the highest mean and median mass loss (EN 113-3 2021) as well as on the x-value (according to CEN/TS 15083-2, 2005)

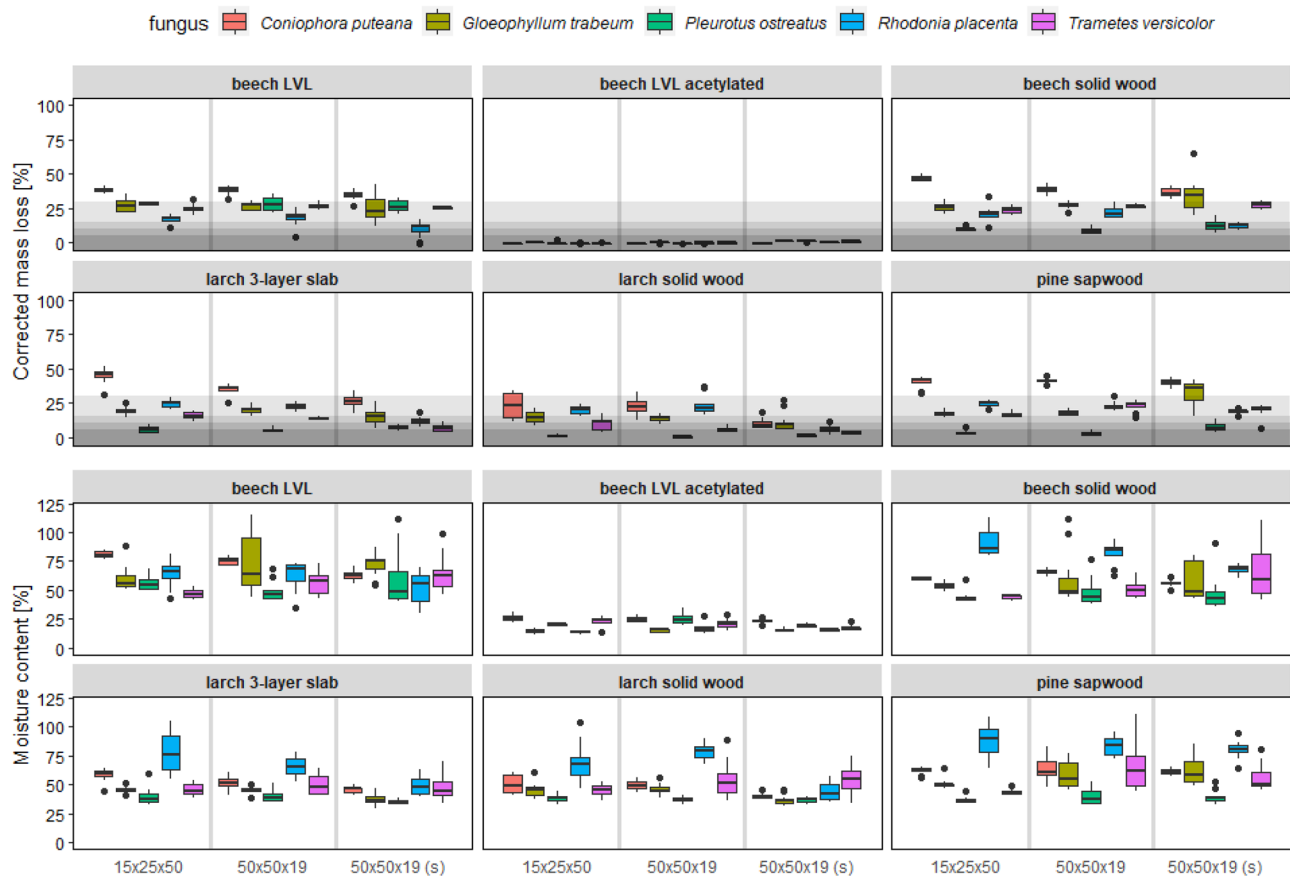| Durability class	Description	Median/mean mass loss	x-value
DC 1	Very durable	ML ≤ 5%	$x \leq 0.10$
DC 2	Durable	5% < ML ≤ 10%	$0.10 < x \leq 0.20$
DC 3	Moderately durable	10% < ML ≤ 15%	$0.20 < x \leq 0.45$
DC 4	Less durable	15% < ML ≤ 30%	$0.45 < x \leq 0.80$
DC 5	Non-durable	ML > 30%	$x > 0.80$

Fig. 2 Boxplots of mass loss (ML) and moisture content (MC) grouped by material and specimen design; (s) = sealed (color figure online)

blocked or modified, (3) micropores in the wood cells are blocked, hindering the fungi to pass and reach the nutrients, (4) hydrolysis of polysaccharides is inhibited because less –OH groups are available, and (5) the MC in the cell wall is insufficiently low for the transport of enzymes of decay fungi (Ringman et al. 2014, 2019; Zelinka et al. 2016, 2022). The theory that acetylation renders wood polymers unrecognizable to fungi was recently debunked (Zelinka et al. 2022). For example, a reduced acetyl content was discovered during the fungal decay of acetylated wood, indicating that fungi were able to remove acetylated wood or cleave off acetyl groups from polymers (Beck et al. 2018; Zelinka et al. 2022). The dominating theory for decay inhibition of acetylated wood seems to be the reduced MC in the cell wall (Zelinka et al. 2022).

As expected, untreated beech and beech LVL references were not durable against almost all used test fungi. The phenol layers in the LVL, which were hypothesized to serve as a chemo-mechanical barrier between two veneer sheets, did not provide adequate protection against the fungi.

The highest ML on both larch solid wood and larch 3-layer slabs was caused by the brown rot fungus *C. puteana*

(Fig. 2 and Table 2). Consequently, DCs were assigned based on this test fungus. Larch solid wood was less durable (DC 4) and larch 3-layer slabs were non-durable (DC 5) each based on the median ML. In contrast, European larch is moderate to less durable (DC 3–4) according to EN 350 (2016). However, the direct comparison in this study showed that acetylated beech is remarkably more durable than one of the conventional cladding and construction materials, be it in the form of solid wood or veneer-based panel.

### 3.3 Effect of specimen design and assessment method on the durability classification

After 16 weeks of incubation, ML varied not only between test fungi and materials, but also between specimen designs (Fig. 2). Generally, the highest ML was achieved with specimens of $15 \times 25 \times 50$ mm^3, followed by unsealed specimens of $50 \times 50 \times 19$ mm^3, and the latter with edge sealant. This ranking was expected since the larger specimens (EN 113-3 2021) had almost the double volume of the smaller specimens (EN 113-2 2021). In addition, the surface–volume ratio (S/V) of the latter was 2.53 and thus higher compared

Table 2 Overview about durability assessments including mean and median mass loss (ML), x-values and decay susceptibility index (DSI)

Material and dimensions (mm³)	Coniophora puteana				Gloeophyllum trabeum				Pleurotus ostreatus				Rhodonia placenta				Trametes versicolor			
	$\bar{x}$ ML	$\tilde{x}$ ML	x-value	DSI	$\bar{x}$ ML	$\tilde{x}$ ML	x-value	DSI	$\bar{x}$ ML	$\tilde{x}$ ML	x-value	DSI	$\bar{x}$ ML	$\tilde{x}$ ML	x-value	DSI	$\bar{x}$ ML	$\tilde{x}$ ML	x-value	DSI
Beech LVL																				
15×25×50	38.8_5	38.8_5	0.9_5	94	27.1_4	26.5_4	1.6_5	151	28.9_4	29.1_4	2.9_5	332	17.3_4	17.7_4	0.7_4	77	24.8_4	24.2_4	1.0_5	102
50×50×19 (s)	34.7_5	35.0_5	0.9_5	87	25.3_4	23.0_4	0.6_4	77	26.7_4	25.8_4	2.1_5	213	9.6_2	11.8_3	0.6_4	51	25.6_4	25.5_4	0.9_5	105
50×50×19	38.2_5	38.3_5	0.9_5	97	26.7_4	27.8_4	1.6_5	159	28.2_4	27.5_4	3.4_5	285	17.7_4	19.1_4	0.8_5	72	26.9_4	26.9_4	1.0_5	105
Beech LVL acetylated																				
15×25×50	-0.9_1	-0.9_1	0.0_1	-2	-0.1_1	-0.2_1	0.0_1	-1	-0.6_1	-0.6_1	-0.1_1	-6	-0.4_1	-0.4_1	0.0_1	-1	-0.5_1	-0.5_1	0.0_1	-1
50×50×19 (s)	-0.5_1	-0.3_1	0.0_1	-2	0.9_1	0.9_1	0.0_1	3	0.8_1	0.8_1	0.1_1	6	0.3_1	0.5_1	0.0_1	2	0.6_1	0.7_1	0.0_1	2
50×50×19	-0.8_1	-0.8_1	0.0_1	-2	-0.1_1	-0.1_1	0.0_1	-1	-0.5_1	-0.5_1	-0.1_1	-6	-0.3_1	-0.2_1	0.0_1	-2	-0.2_1	-0.2_1	0.0_1	-2
Beech solid wood																				
15×25×50	46.9_5	46.2_5	1.1_5	94	25.9_4	25.7_4	1.6_5	155	10.1_3	10.2_3	–		21.1_4	20.8_4	0.8_5	96	23.7_4	23.5_4	–	
50×50×19 (s)	36.4_5	35.9_5	0.9_5	91	34.5_5	34.1_5	1.0_5	105	12.5_3	12.2_3	–		12.6_3	13.1_3	0.7_4	66	24.4_4	27.4_4	–	
50×50×19	38.6_5	38.7_5	0.9_5	117	27.5_4	27.5_4	1.6_5	152	8.5_2	8.0_2	–		22.1_4	20.5_4	0.9_5	87	26.5_4	26.2_4	–	
Larch 3-layer slab																				
15×25×50	44.7_5	46.1_5	1.1_5	84	19.2_4	19.2_4	1.2_5	152	5.7_2	5.5_2	0.5_4	59	24.5_4	24.8_4	1.0_5	97	15.8_4	15.7_4	0.7_4	52
50×50×19 (s)	26.3_4	25.8_4	0.6_4	66	15.0_4	14.9_3	0.4_3	46	7.1_2	7.4_2	0.6_4	57	11.9_3	11.3_3	0.6_4	64	6.7_2	6.0_2	0.2_3	28
50×50×19	34.3_5	35.9_5	0.9_5	111	26.9_4	27.5_4	1.1_5	113	5.0_1	4.6_1	0.6_4	57	22.4_4	22.3_4	1.0_5	101	13.7_3	13.6_3	0.5_4	67
Larch solid wood																				
15×25×50	23.1_4	23.2_4	0.6_4	56	14.7_3	14.7_3	0.9_5	78	0.7_1	0.7_1	0.1_1	5	19.8_4	20.5_4	0.8_5	101	9.7_2	10.9_3	0.5_4	22
50×50×19 (s)	9.8_2	8.2_2	0.2_3	25	11.0_3	9.4_2	0.3_3	34	1.2_1	1.5_1	0.1_2	10	5.8_1	5.7_2	0.3_3	31	3.2_1	3.4_1	0.1_2	13
50×50×19	22.8_4	22.3_4	0.5_4	57	13.9_3	14.3_3	0.8_5	86	0.4_1	0.2_1	0.0_1	7	23.1_4	21.6_4	1.0_5	82	5.8_2	5.2_2	0.2_2	41
Scots pine sapwood																				
15×25×50	40.1_5	41.4_5	–		17.1_4	16.5_4	–		3.1_1	2.6_1	0.3_3	34	24.1_4	24.7_4	–		16.5_4	16.4_4	0.7_4	87
50×50×19 (s)	39.9_5	39.8_5	–		32.8_5	35.9_5	–		7.5_2	6.9_2	0.6_4	60	18.7_4	18.8_4	–		19.5_4	20.6_4	0.8_4	80
50×50×19	41.0_5	41.0_5	–		17.7_4	17.7_4	–		2.9_1	2.6_1	0.3_3	31	23.0_4	22.6_4	–		23.0_4	23.8_4	0.9_5	70

The durability classes (DC) are shown as subscript numbers

$\bar{x}$ ML mean mass loss in %, $\tilde{x}$ ML median mass loss in %, DSI in %, s sealed

Fig. 3 Relationship between surface–volume ratio (*S/V*) and mean mass loss (ML) of six materials after 16 weeks of incubation to five selected fungi. The mean values are shown without the standard deviation for clarity (color figure online)
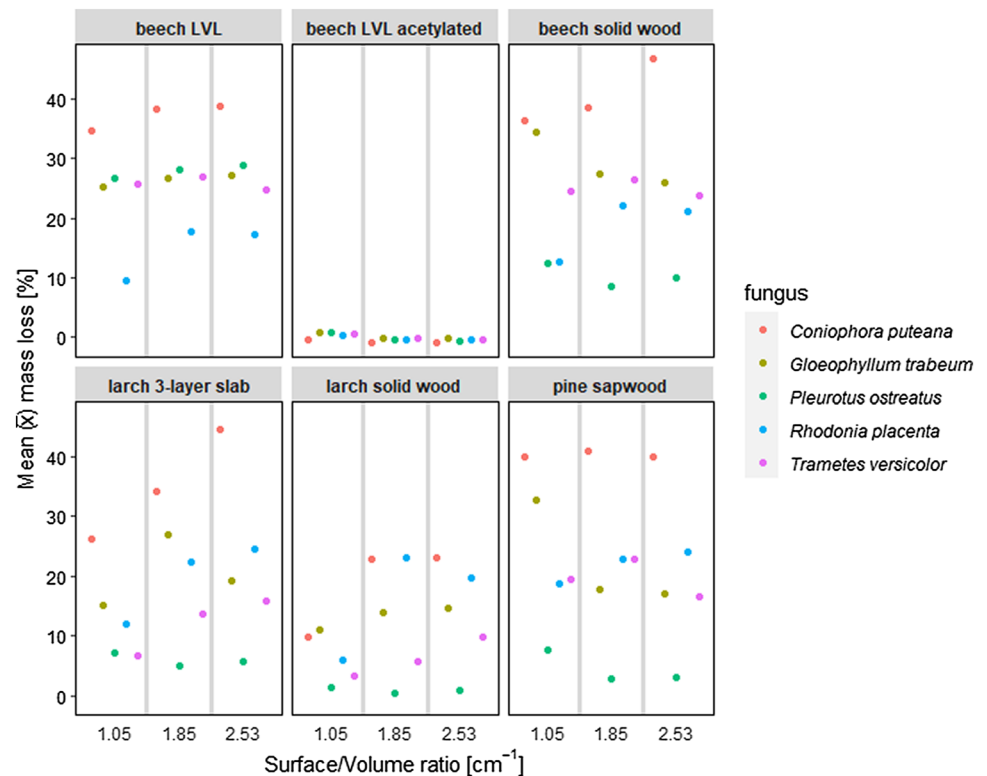
to 1.85 for the unsealed and 1.05 for the sealed specimens of $50 \times 50 \times 19$ mm³.

In this study, an increased *S/V* was also frequently associated with an increased ML (Fig. 3). However, for some combinations, the opposite was found. Samples with a *S/V* of 1.05 showed greater ML than specimens with a surface to volume ratio of 2.53.

In a previous study, Brischke et al. (2021) compared the effect of different specimen sizes and geometries on the ML, *x*-values and resulting DCs of European larch heartwood. Their results showed that ML is well correlated with the specimens' *S/V*. Maximum ML was achieved with specimens having a *S/V* between 3 and 5. Since both specimen designs with the size of $50 \times 50 \times 19$ mm³ (with and without sealant) had smaller *S/V* compared to the EN 113-2-specimens, it was not surprising that both ML and *x*-values were smaller, but DCs partly higher. Differences in DCs between the three specimen designs were only few, which might be explained with the tested materials being either 'very durable' (i.e. acetylated beech and beech LVL) or 'non-durable' (i.e. Scots pine sapwood, beech, beech LVL). Solely the larch materials were supposed to be 'less to moderately durable'. As can be seen from the range of ML and *x*-values respectively for the different DCs in Table 1, the probability to end up with a different DC at a given shift in ML is higher within DC 2 and 3 compared to DC 1, 4, and 5. Consequently, the effect of the specimen geometry was more prominent with larch solid wood and the larch 3-layer slab.

In addition to the varying *S/V*, the specimens had different portions of end-grain surface which allows for longitudinal penetration of the fungal hyphae, which is the preferred anatomical direction for both fungal growth and water transport (Brischke and Alfredsen 2020; Huckfeldt and Schmidt 2015). Hence, lower ML and thus higher durability of the edge-sealed specimens can be explained with the entire exclusion of longitudinal pathways.

Leaching of test specimens prior to fungal exposure can affect the ML through fungal decay (Aloui et al. 2004; Curling and Murphy 1999). Therefore, ML by leaching was determined and compared between the different specimen designs (Fig. 4). The relative ML by leaching was not significantly different between specimens of $50 \times 25 \times 15$ mm³ and $50 \times 50 \times 19$ mm³. This suggests that the leaching of water-soluble compounds may only be a minor contributor to differences in durability between specimens of varying volumes.

The median and mean ML correlated perfectly (Fig. 5). In only four out of 30 cases the classification differed by one DC, but in both directions (Table 2). This coincides with previous studies (Bollmus et al. 2014; Brischke et al. 2022) where only marginal differences in durability classification were found between the use of mean and median ML as a basis. However, the use of the median ML for durability classification shall be preferred since it diminishes the effect of outliers. Furthermore, it should also be the basis

Fig. 4 Mass loss during leaching (Δm_L) after 2 weeks of storing in water based on EN 84 (2020)
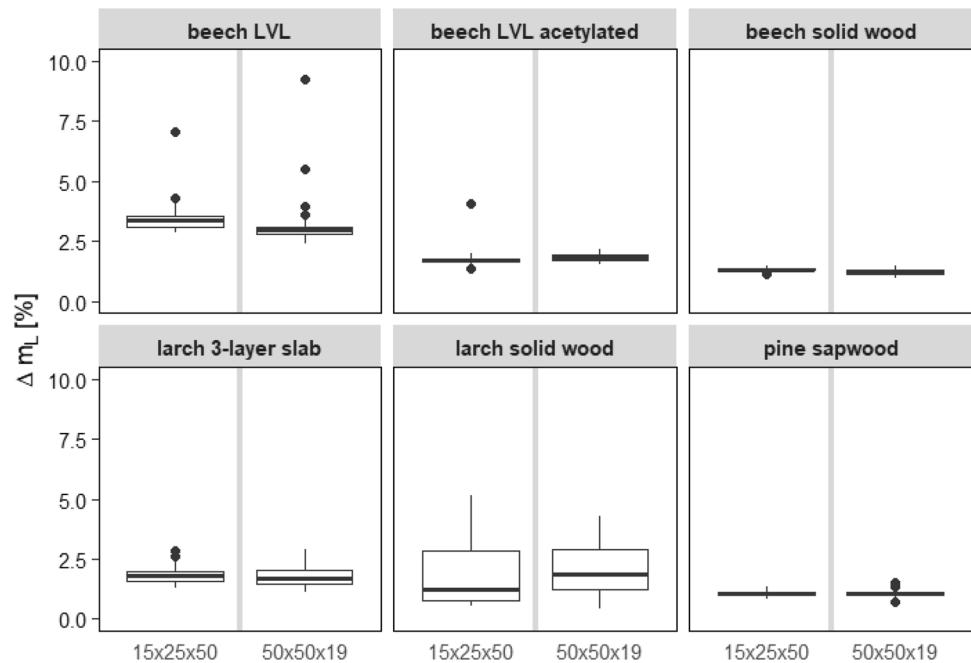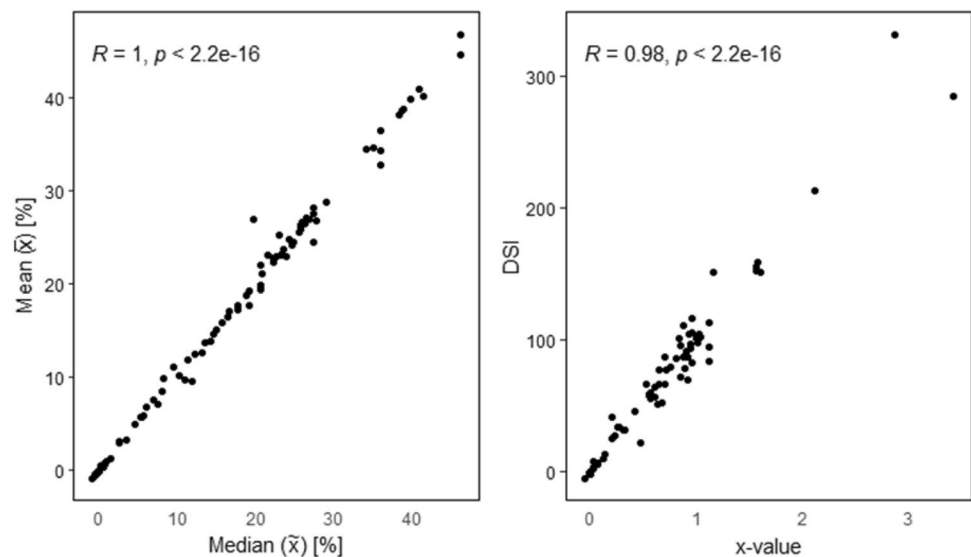

Fig. 5 Positive Pearson correlation for mean and median mass loss (ML), as well as for the decay susceptibility index (DSI), and the x-value (color figure online)

for calculating x-values, DSI, and other derived parameters serving as the basis for assigning DCs.

The DSI is not meant to use as the basis for durability classification. However, a few attempts to achieve this have been made. For instance, Bicke (2019) compared DCs of chemically modified timber on the basis of the mean ML (x-values) and the DSI, where the use of the latter led rather often to lower durability. The DSI was not classified for durability in this study, but it correlated well with the x-value (Fig. 5).

4 Conclusion

The arithmetic mean and median percentage ML, the x-values, and the DSI were used to assess the durability of acetylated beech LVL using three specimen geometry designs against five wood-destroying basidiomycete monocultures. Acetylation of beech veneers with acetic anhydride highly improves the durability of the manufactured LVL. The material was assigned to DC 1 independent of the applied specimen design and shape as well as test fungi. References like solid larch wood were less durable (DC 4) in comparison.

A chemo-mechanical barrier against wood-destroying fungi between the veneer layers was not provided by the phenol adhesive, as evidenced by the fact that the sealed reference LVL was not durable (DC 5).

The mass loss was influenced by the sample size; essentially, the smaller the *S/V* ratio, the greater the mean and median mass loss. The tested larch solid wood and 3-layer slab demonstrated this effect the most. The leaching of water-soluble components appears to be a small contributor to this effect.

The DC was impacted by the assessment method, and to prevent outliers, median mass loss over mean mass loss should be calculated. Considering their strong correlation, the *x*-value DC assessment method could be used as a basis to categorize the DSI.

Even though it was found that the shape and specimen design impact on the ML during fungal decay, more representative materials like chipboards, MDF, OSB, and plywood should be tested to validate and better quantify these effects.

Overall, it can be stated that acetylated beech LVL is very durable (DC 1) against wood-destroying fungi. Due to the reduced wood-moisture interaction the dimensional stability is also improved compared to unmodified LVL. This might cause less cracks during outdoor exposure on the material. Moreover, the mechanical properties are relatively high compared to LVL made out of softwood species.

However, the increased density due to additional acetyl groups and high production costs can be seen as possible drawbacks. Moreover, swelling and shrinking continue to occur despite the high ASE. This needs to be considered during outdoor exposure due to moisture changes, which requires a though bonding to avoid delamination.

It is suggested to evaluate the performance of the material in real-life scenarios. One such real-life example might involve exposing acetylated beech LVL outdoor for several years at different locations. Thus, factors like weathering, UV radiation, and moisture changes have an impact on the material. Moisture traps could be taken into consideration to intensify the test.

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Declarations

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