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Impact of Acetylation on the Behaviour of Single-Dowel Timber Connections

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Abstract: This paper presents an experimental study where the mechanical behaviour of single-dowel timber connections made of acetylated Scots pine is compared with the behaviour of connections made from untreated Scots pine. The main aim was to evaluate the influence of the acetylation on the connection brittleness and also to compare the experimental results to the design provisions of the current European structural timber code, Eurocode 5 (EC5). The experiments included embedment tests and tests with connections loaded parallel and perpendicular to the grain, and, for the latter tests, applying different end and edge distances. The acetylated wood showed a 2% increase in density and a 31% increase in embedment strength compared to the untreated wood. For tests on connections loaded parallel to the grain, all specimens made from acetylated wood failed in a brittle manner, while the connections made from untreated wood and complying with minimum end distance of the EC5 design provisions failed due to embedment failure followed by splitting involving cracking along the grain. The connections made of acetylated wood showed a 13–15% higher capacity than the corresponding specimens made from untreated wood. Thus, to fully utilize the potential of the increased embedment strength parallel to the grain, it is concluded that reinforcement of the joint, e.g., by self-tapping screws or externally applied sheet reinforcement would be necessary if the minimum end distances of EC5 are applied. The current design provisions for loading perpendicular to the grain overestimated the capacities severely with predicted characteristic values being 20–50% higher than mean values from tests for the recommended minimum edge distances. Finally, it was found that the splitting capacity in loading perpendicular to the grain was 10–18% lower for the specimens made from acetylated wood compared to the untreated wood.

Keywords: dowel-type connections; wood fracture; brittle failure; splitting; Scots pine; acetylated wood

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1. Introduction

1.1. Background and Motivation

Tensile stresses perpendicular to the grain should be avoided in the design of timber structures, but this is not always possible. Figure 1 illustrates a dowel-type connection loaded perpendicular to the grain, which can fail by splitting due to crack initiation and propagation along the grain [1,2].

Based on linear elastic fracture mechanics (LEFM), a design criterion for the verification of joints loaded perpendicular to the grain is implemented in Eurocode 5 (EC5) [3], stating that the maximum shear force at the connection, $F_{v,Ed}$, should satisfy

$$F_{v,Ed} \leq F_{90,Rd}$$
$$F_{v,Ed} = \max(F_{v,Ed,1}, F_{v,Ed,2}) \quad (1)$$

with definitions according to Figure 1. The characteristic shear force capacity, $F_{90,Rk}$, for a connection with a metal dowel-type fastener is according to EC5 determined by [3]

$$F_{90,Rk} = 14b\sqrt{\frac{h_e}{1-\frac{h_e}{h}}} \tag{2}$$

with b, h, and h_e, being defined in Figure 1.

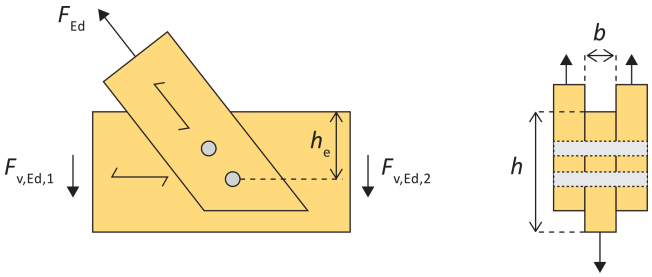


Figure 1. Dowel-type connection loaded perpendicular to the grain.

This design criterion involves, seemingly, only geometry parameters for the calculation of the shear force capacity of the joint. However, Equation (2) originates from the work of [4–7] and was in [4] suggested as

$$F_{90,Rk} = b\sqrt{\frac{G_c G}{0.6}}\sqrt{\frac{h_e}{1-\frac{h_e}{h}}} \tag{3}$$

where G_c is the critical energy release rate and G is the longitudinal shear modulus, and where b, h, and h_e are defined in Figure 1. Comparing Equations (2) and (3), it is clear that assumptions regarding linear elastic fracture properties are implicitly included in Equation (2). Consequently, its applicability to different wood species and modified wood remains to be verified.

When designing dowel-type connections loaded parallel to the grain, brittle failure modes as those illustrated in Figure 2 must be taken into account. In EC5 [3], the design is based on the Johansen yield theory [8], which assumes ductile failure modes by plastic deformations of the dowel and/or the timber. In addition, minimum edge and end distances are given in the code, together with a reduction factor of the effective number of dowels in a row. Altogether, these requirements are aimed at avoiding the brittle failure modes due to splitting along the grain (see, e.g., the work of Jorissen [9]).

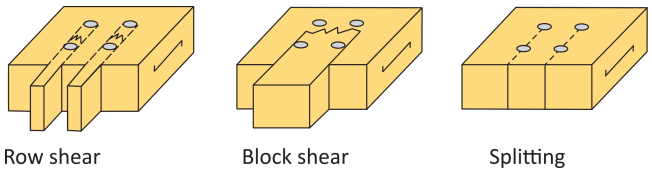


Figure 2. Brittle failure modes for dowel-type connections loaded parallel to the grain.

Since different wood species have different strength, stiffness, and fracture energy (see, e.g., [10]), their material brittleness also varies. In addition, wood modification techniques, such as heat treatment or acetylation are known to alter, among other things, the fracture energy of the material [11]. Consequently, there is a need to verify or adapt the current design criteria for materials showing a markedly different material brittleness compared to the material brittleness of materials included in the current EC5.

In conclusion, it can be stated that the current design approach of EC5 for dowel-type joints implicitly includes the fracture energy of the wood as a material property. Consequently, those design provisions should be used cautiously for situations involv-

ing materials having a markedly different fracture energy than the implicitly assumed fracture energy.

1.2. Previous Work

Acetylated wood was used in this study in order to achieve a material with increased brittleness relative to the reference (untreated) material. Acetylation is a chemical modification technique known to increase both the durability and dimensional stability of wood thanks to the reduced hygroscopicity of the modified material. However, since the chemical constitution of the cell wall polymers is changed, mechanical properties are also affected. Through acetylation, density increases, and typically the hardness, compression strength (parallel and perpendicular to the grain), and modulus of rupture (MOR) increase, while the modulus of elasticity is only marginally influenced (see, e.g., [12–14]). In [12], the influence on the apparent shear strength parallel to the grain (clear wood specimens tested according to ASTM D143 [15]) and on the toughness (subjecting 1/2- by 1/2- by 5-inch specimens to a sharp blow using a falling pendulum) was reported. Reductions in shear strength of 21, 12, and 24% were found for ponderosa pine, red oak, and sugar maple, respectively. The toughness for ponderosa pine *increased* after acetylation by 17.5%, it decreased by 7% for red oak, and there was no influence on toughness for sugar maple [12].

For dowel-type joints, an increased material brittleness is important to consider due to the occurrence of stress concentrations which may lead to crack initiation, propagation, and sudden collapse [16]. In previous studies, e.g., [11,17–19], investigations on the fracture energy of acetylated wood have been performed. These studies have demonstrated that acetylated wood shows a significantly decreased fracture energy, i.e., it becomes more brittle. In a recent study [20], it was shown that the MOE and the MOR of spruce wood were affected "to some extent" by acetylation (for both these properties, the effect was in the range of a 10% increase). One study on dowel-type joints on acetylated wood was presented in [21]. In that study, there was no comparison performed with untreated material, making it impossible to quantify the effect of the acetylation. Furthermore, the study included three different dowel diameters but only one edge distance for each diameter ($6d$), making it impossible to see any possible effect of the acetylation on the failure mode of the joint. The main conclusions from that study were that the behaviour of the acetylated timber seemed more brittle than untreated wood, that applying the EC5 design formulae did not give accurate predictions of the load-bearing capacity, and that the failure modes of the dowel-type joints were always brittle (no embedment failures were noted). A recent study on acetylated birch plywood by Wang et al. [22] included the influence of dowel diameter on the embedment strength of dowel-type joints. Apart from these studies, the topic of dowel-type joints in acetylated wood seems not have been researched to any greater extent.

1.3. Aim

The aim of this paper is to present the results of an investigation on the mechanical behaviour of single-dowel joints made of acetylated wood and in particular the influence of material brittleness on connection behaviour, for various loading directions relative to the grain, and for various edge distances. To the authors knowledge, such comparisons have not been reported previously. Furthermore, the aim is to compare the experimental results to the design provisions of the current European structural timber code, EC5, in order to quantify the influence of the acetylation and the increased material brittleness it brings on the load-bearing capacity of the connection and the brittleness of the connection. Based on this and the knowledge about the material brittleness of acetylated wood gained in previous investigations [11,19], the overarching long-term goal of the research is to formulate design approaches for acetylated wood and other wood species showing a high degree of material brittleness, including design of multi-dowel joints.

2. Materials and Methods

2.1. Material

Timber members of both untreated and acetylated Scots pine (*Pinus sylvestris*) were used. The material was taken from a single delivery (one pallet) of timber delivered by the sawmill Isojoen Saha, located in Finland. The modified boards were acetylated in a proprietary industrial-scale process at Accys Technology in Arnhem, the Netherlands, using the standard process used for the commercial production process of Accoya radiata pine (European Patent No. 2818287A1 [23]). For practical and economical reasons, only a very limited amount of timber could be processed and no adjustments were made to the acetylation process regarding neither time, temperature, nor concentration of chemicals.

The acetylated boards were analysed using near-infrared spectroscopy [24], and the acetyl content was found to be approximately 20%. Before testing, specimens were stored in a climate chamber with a relative humidity of 60% and a temperature of 20 °C, until reaching moisture equilibrium. The mean densities of the untreated and the acetylated boards after conditioning were 484 kg/m^3 and 493 kg/m^3, respectively. For the untreated wood, the moisture content determined by the oven-dry method was 10%. The moisture content of the acetylated wood was approximately 3.4%, determined with the same method and taking into account the increase in dry mass which comes as a consequence of the acetylation [25].

2.2. Embedment Strength

The embedment strength parallel and perpendicular to the grain was determined for the untreated and the acetylated Scots pine. For each direction and material, four samples were examined. Specimens were tested according to Figure 3, i.e., in accordance with ISO/FDIS 10984-2 [26]. The load was applied at a rate of 1 mm/min by a displacement-controlled movement of the crosshead of the testing machine. The displacement of the dowel was considered by averaging $\delta_{1,1}$ and $\delta_{1,2}$ (see Figure 3). Specimens were loaded until failure or until the displacement reached 5 mm. The ultimate load P_u was defined as the load at failure or the maximum load reached within 5 mm of displacement. The embedment strength $f_{h,\alpha}$ was calculated as

$$f_{h,\alpha} = \frac{P_u}{td} \tag{4}$$

where t is the thickness of the specimen, and d the diameter of the dowel. Here, $d = 12$ mm was used.

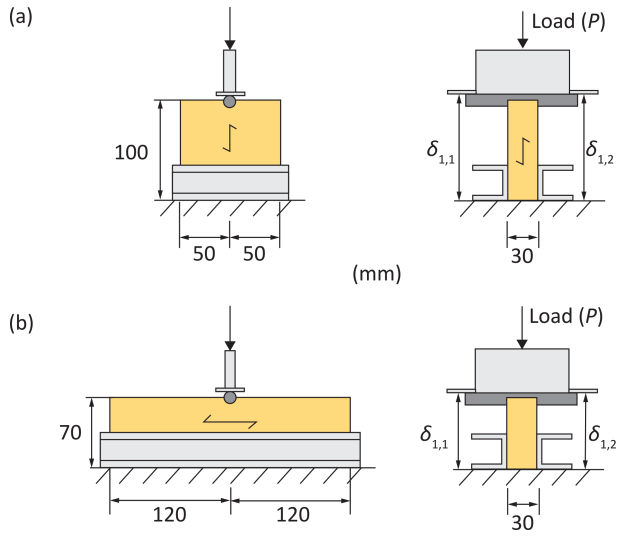


Figure 3. Test setup for determination of embedment strength (**a**) parallel and (**b**) perpendicular to the grain according to ISO/FDIS 10984-2 [26] with a dowel with a diameter of 12 mm.

2.3. Dowel-Type Connections

Dowel-type connections loaded parallel and perpendicular to the grain were tested (see Figures 4 and 5).

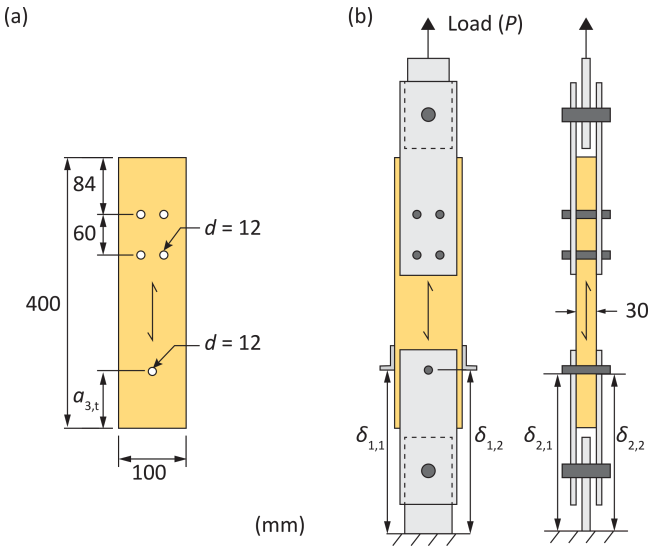


Figure 4. Geometry of specimens (**a**) and test setup (**b**) for dowel connections loaded parallel to the grain, where the load (P) was applied with an end distance $a_{3,t}$ to the loaded edge.

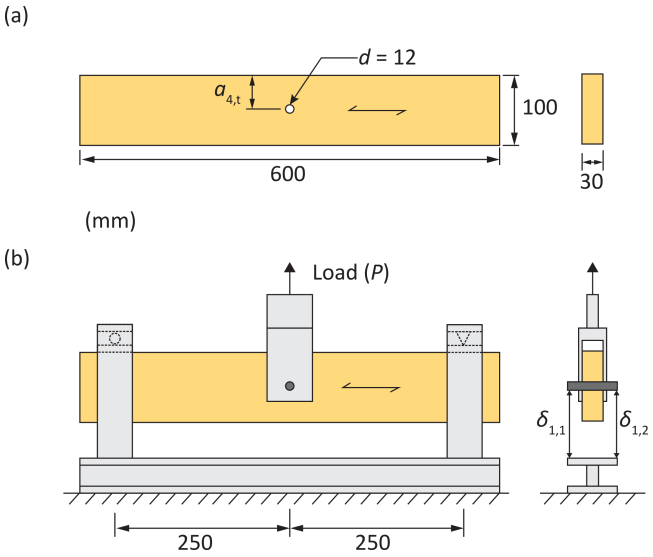


Figure 5. Geometry of specimens (**a**) and test setup (**b**) for dowel connections loaded perpendicular to the grain with the load (P) applied at an edge distance $a_{4,t}$.

In order to promote brittle failure modes and avoid plasticity in the fasteners, the timber members were assigned a sufficiently small thickness in relation to the dowel diameter. A dowel with a diameter $d = 12$ mm was used in all tests. No bending of the dowel was identified during or after testing. A material testing system (MTS322 Test Frame) was used, and the load was recorded by a load cell (MTS 500 kN) with a resolution of 0.005 kN. Displacements were recorded by LVDT sensors (RDP ± 10 mm) with a resolution of 0.003 mm. The load was applied at a rate of 1 mm/min by displacement-controlled movement of the crosshead of the testing machine.

2.3.1. Parallel to the Grain Loading

To prevent brittle failures for dowel-type connections loaded parallel to the grain, a minimum end distance $a_{3,t}$ is prescribed by EC5 [3] according to

$$a_{3,t} = \max(7d, 80\ \text{mm}) \tag{5}$$

where d is the diameter of the dowel. For the present study, this means a minimum end distance $a_{3,t} = 7d = 84$ mm.

For the dowel connections loaded parallel to the grain (see Figure 4) three end distances were studied for each test group (cf. Table 1). When deciding on the end distances to test, the starting point was the $7d$ of EC5. For this end distance, the acetylated specimens already behaved in a brittle manner. Thus, it was not considered of any interest to test smaller values of $a_{3,t}$, considering also the limited amount of material available to the research project. Instead, larger values were tested ($9d$ and $11d$). In regard to the untreated material, the EC5 value $a_{3,t} = 7d$ gave a result of moderately brittle; however, to also ensure a set of tests with more pronounced brittle behaviour, $a_{3,t} = 5d$ was also tested.

Deformations were measured in line with the dowel and considered by the average of displacements $\delta_{1,1}$ and $\delta_{1,2}$. To verify that no bending of the dowel occurred, displacements $\delta_{2,1}$ and $\delta_{2,2}$ were also monitored.

Table 1. The number of specimens tested in loading parallel to the grain for each end distance $a_{3,t}$. According to EC5, the minimum end distance is $a_{3,t} = 7d$ (d = 12 mm).

$a_{3,t}$	**5*d***	**7*d***	**9*d***	**11*d***
Untreated	4	4	4	-
Acetylated	-	4	4	4

2.3.2. Perpendicular to the Grain Loading

For loading at an angle to the grain, EC5 prescribes a minimum edge distance $a_{4,t}$ according to the following:

$$a_{4,t} = \max((2 + 2\sin\alpha)d, 3d) \tag{6}$$

where d is the diameter of the dowel, and α the angle between the loading direction and the grain. Consequently, since 12 mm dowels were used, the minimum edge distance is $a_{4,t} = 4d = 48$ mm.

Two edge distances were considered in the perpendicular to the grain tests (see Figure 5) and the number of specimens within each test group is presented in Table 2. The load, P, was applied by the displacement-controlled movement of the crosshead of the testing machine at a rate of 1 mm/min, and the specimens were loaded until failure. Locations of extensometers used are shown in Figure 5. The displacement of the dowel was considered by averaging $\delta_{1,1}$ and $\delta_{1,2}$.

Table 2. The number of specimens tested in loading perpendicular to the grain for each edge distance $a_{4,t}$. According to EC5, the minimum edge distance is $a_{4,t} = 4d$ (d = 12 mm).

$a_{4,t}$	**4*d***	**5.33*d***
Untreated	4	4
Acetylated	4	4

2.3.3. Evaluation of Connection Brittleness

In this study, a ductility measure D_f according to [27] (displacement capacity of the post-linear elastic response) was applied:

$$D_f = \frac{u_f}{u_y} \tag{7}$$

Here, u_f is the displacement at failure, and u_y is the displacement at the yielding point. In this study, failure of a specimen was defined by a $\geq$ 20% load decrease from the maximum load. The yielding point was defined according to Figure 6, i.e., by the intersection of the load–displacement response and the linear elastic response offset 0.1 mm. The linear elastic response was in turn defined by the slope k_e of a linear regression fit for load values between 40% and 60% of the maximum load.

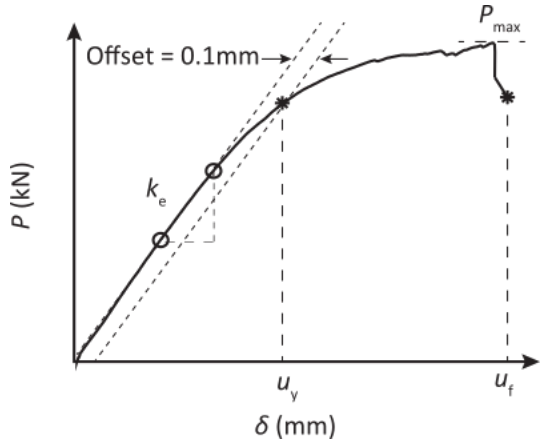


Figure 6. Definition of yielding point (u_y) and failure point (u_f) for a typical load (P) versus displacement (δ) response, where P_{max} is the maximum load and k_e is the linear elastic slope.

In the literature, various definitions for the yielding point and the failure point have been suggested, e.g., by defining the failure displacement as the displacement at maximum load. The approach used herein was chosen to quantify the displacement capacity also for cases involving a slightly diminishing load bearing capacity after maximum load. To categorise the ductility of the load–displacement responses, classifications based on the value of D_f, according to [27] were used. Thus, the higher bounds for brittle, low ductility and moderate ductility were set to $D_f = 2$, 4, and 6, respectively, and $D_f > 6$ is categorised as high ductility.

In regard to quantifying the brittleness of a structure from a theoretical point of view, a brittleness ratio has been used [28]:

$$\frac{d}{l_{ch}} = \frac{f^2 d}{E G_f}. \tag{8}$$

Here, d is a measure of the structure's size, l_{ch} is the so-called characteristic length of the material, f is a measure of the material strength, E represents the material stiffness (moduli of elasticity and shear moduli), and G_f is the specific fracture energy for the relevant mode of failure. l_{ch} is a measure of the ductility of the material in the sense that the larger the characteristic length, the more ductile the material. It is of special interest to note that the value of l_{ch} is determined by a *ratio* involving the material parameters E, G_f, and f. Furthermore, note that the brittleness of the *structure* is governed also by its size, d. In the current study, the influence of the *material* brittleness is the main concern and defining this by l_{ch} in Equation (8) helps to generalise the conclusions drawn, as l_{ch} is a *ratio* of material parameters. As an example, doubling the strength of the material would have the same effect as halving (simultaneously) both the stiffness and the specific fracture

energy. Likewise, the same effect would be obtained by increasing the size of the structure by a factor of four (length scale).

2.4. Comparison with Eurocode 5

To assess whether current the EC5 design provisions are appropriate for acetylated wood, results for the examined dowel-type connections were evaluated against EC5 predictions. In EC5, the characteristic embedment strength, $f_{h,\alpha,k}$ in N/mm^2, at an angle to the grain, α, is given by the following [3]:

$$f_{h,\alpha,k} = \frac{f_{h,0,k}}{k_{90}\sin^2\alpha + \cos^2\alpha} \tag{9}$$
$$f_{h,0,k} = 0.082(1 - 0.01d)\rho_k$$
$$k_{90} = \begin{cases} 1.35 + 0.015d \text{ (for softwoods)} \\ 1.30 + 0.015d \text{ (for laminated veneer lumber)} \\ 0.90 + 0.015d \text{ (for hardwoods)} \end{cases}$$

where ρ_k is the characteristic density in kg/m^3, and d is the diameter of the dowel in mm. Note that according to Equation (9), the predicted embedment strength is not influenced by k_{90} for $\alpha = 0$, and thus the embedment strength parallel to the grain is assumed to be proportional to the (characteristic) density. In this study, experimental results were compared with calculated values based on the EC5 formulae, applying the value of k_{90} for softwoods and using the mean densities of the untreated and acetylated Scots pine (after conditioning the specimens at a relative humidity of 60% and a temperature of 20 °C, see Section 2.1).

Based on the embedment strength, the load-bearing capacity of a dowel-type connection can be estimated. As the connections studied herein were designed to avoid plasticity in the fasteners, the governing failure mode should be embedment failure according to the Johansen yield theory or brittle failure modes. According to EC5, and for the current test setups, the characteristic load-bearing capacity associated with embedment failure, $F_{v,Rk}$, is given by [3]

$$F_{v,Rk} = f_{h,\alpha,k} t d. \tag{10}$$

For dowel-type connections loaded parallel to the grain, the only brittle failure mode covered in EC5 is block shear (cf. Figure 2). As described in Annex A of EC5 [3], the load-bearing capacity is restricted due to block shear by

$$F_{bs,Rk} = \max\begin{cases} 1.5 A_{net,t} f_{t,0,k} \\ 0.7 A_{net,v} f_{v,k} \end{cases} \tag{11}$$

where $f_{t,0,k}$ is the characteristic tensile strength parallel to the grain, and $f_{v,k}$ the characteristic shear strength. Both these nominal strengths are most likely affected by the brittleness of the material. For dowel-type connections, $A_{net,t}$ and $A_{net,v}$ are the effective areas of the head tensile plane and the lateral shear planes, respectively. For loading perpendicular to the grain, splitting is considered in EC5 by Equation (2).

3. Results

3.1. Embedment Strength

The embedment strength is primarily affected by species or type of product, density, and dowel dimension. Since acetylation of wood is associated with an increased density, an increased embedment strength for acetylated wood would be expected. Results from this study are given in Table 3, presenting mean values of the embedment strength parallel and perpendicular to the grain ($f_{h,\alpha,m}$), along with values estimated based on the mean density and Equation (9) ($f_{h,\alpha,EC5}$ (softwood)). As expected, when comparing acetylated and untreated wood in loading parallel to the grain, a significantly increased embedment

strength was found for the acetylated wood. For loading perpendicular to the grain, no significant difference was found; thus, the embedment strength perpendicular to the grain can be considered unaltered. The statistical significance of the difference was evaluated using Student's *t*-test, assuming unequal variance for the untreated and acetylated specimens.

Table 3. Test results and EC5 estimates of the embedment strength $f_{h,\alpha}$ in (MPa) and the ratio $\beta = f_{h,\alpha,EC5}/f_{h,\alpha,m}$. The difference in embedment strength between untreated and acetylated wood, $\Delta f_{h,90}$, is marked (*) if significant (using Student's *t*-test assuming unequal variance $p < 0.05$).

		$f_{h,\alpha,m}$	$f_{h,\alpha,EC5}$	β
Parallel ($\alpha = 0°$)	Untreated	36	35	0.97
	Acetylated	47	36	0.76
	$\Delta f_{h,0}$	+ 31% * ($p = 0.0138$)		
Perpendicular ($\alpha = 90°$)	Untreated	24	23	0.95
	Acetylated	26	23	0.89
	$\Delta f_{h,90}$	+8%		

Comparing the test results with the EC5 predictions, a parameter β was introduced, representing the embedment strength based on the EC5 approach divided by the experimentally found mean embedment strength.

3.2. Parallel to the Grain Loading

The load–displacement responses for the dowel connections loaded parallel to the grain are shown in Figure 7, and the mean ductility D_f for each test group is presented in Table 4.

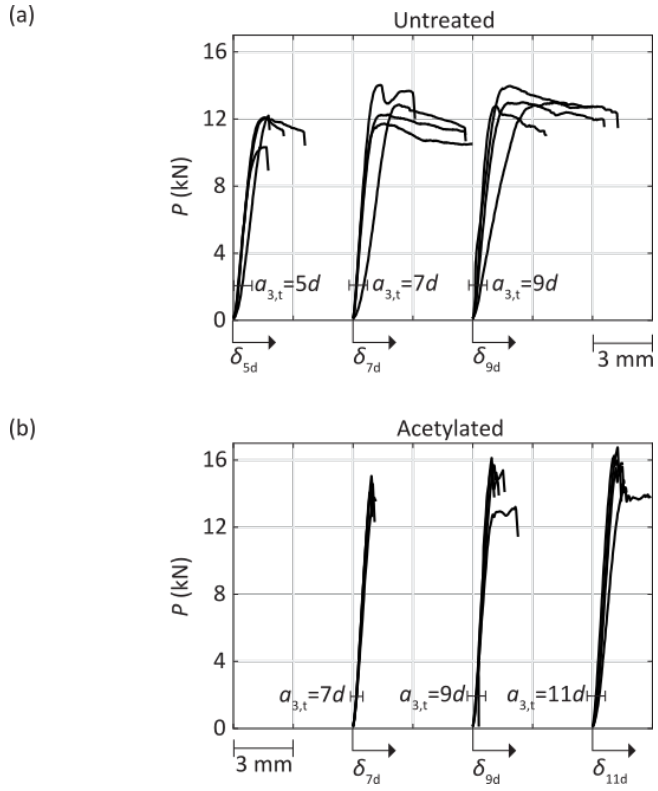


Figure 7. Load–displacement responses for dowel-type connections loaded parallel to the grain for untreated (**a**) and acetylated wood (**b**) with varying end distances $a_{3,t}$ ($d = 12$ mm).

Table 4. Ductility, D_f, evaluated for dowel-type connections loaded parallel to the grain.

$a_{3,t}$	**5*d***	**7*d***	**9*d***	**11*d***
Untreated	2.2	5.0	4.9	-
Acetylated	-	1.1	1.7	1.7

For untreated wood (Figure 7a) with the recommended minimum end distance $a_{3,t} = 7d$, the response was classified as *moderately ductile* ($D_f = 5$), attributed to embedment failure followed by splitting (Figure 8a). An increased end distance, $a_{3,t} = 9d$, did not have a considerable effect on the ductility, while a decreased end distance, $a_{3,t} = 5d$, resulted in responses classified by low ductility. For acetylated wood (Figure 7b) and using the minimum end distance $a_{3,t} = 7d$, brittle failures ($D_f = 1.1$) were found. Increasing the end distance ($a_{3,t} = 9d, 11d$) increased the ductility, but failures were still considered brittle ($D_f \leq 2.0$). Examples of failed specimens are shown in Figure 8. The primary failure mode for acetylated wood was block/row shear, as shown in Figure 8b. This feature has also been indicated in a previous study of acetylated wood [21], where brittle failure modes attributed to block/row shear dominated.

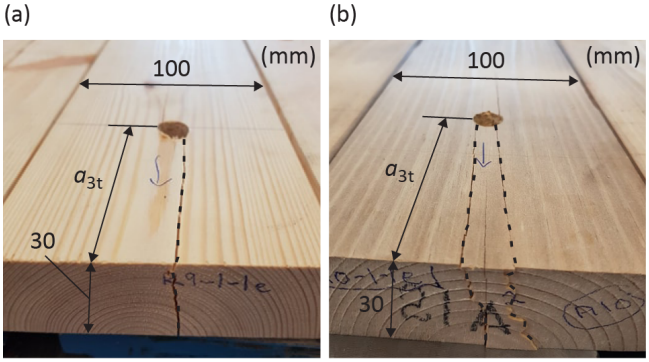


Figure 8. Typical failure modes observed: for untreated wood, splitting occurred (**a**), while block/row shear was observed for acetylated wood (**b**).

Mean values of the load-bearing capacity for the connections loaded parallel to the grain, $F_{0,m}$, are presented in Table 5. When comparing the load-bearing capacity of connections made from untreated and acetylated wood, the acetylated wood demonstrated a significantly increased load-bearing capacity (Student's *t*-test, assuming unequal variance for the untreated and acetylated specimens, $p < 0.05$). This was an expected result, in line with the previously mentioned observation of an increased embedment strength parallel to the grain for the acetylated samples.

Table 5. Mean load-bearing capacity for connections loaded parallel to the grain, $F_{0,m}$ in (kN). The ratio β represents the EC5 estimation (Equation (10) based on either the mean or the EC5 estimate of the embedment strength) divided by the mean load-bearing capacity. The difference in load-bearing capacity between untreated and acetylated wood $\Delta F_{0,m}$ is marked (*) if significant using Student's *t*-test assuming unequal variance ($p < 0.05$).

$a_{3,t}$		**5*d***	**7*d***	**9*d***	**11*d***
Untreated	$F_{0,m}$	11.7	12.7	13.2	-
	β_m	1.1	1.0	0.98	-
	β_{EC5}	1.1	0.99	0.95	-
Acetylated	$F_{0,m}$	-	14.4	15.2	15.7
	β_m	-	1.2	1.1	1.1
	β_{EC5}	-	0.89	0.84	0.82
$\Delta F_{0,m}$			+13% * ($p = 0.0322$)	+15% * ($p = 0.0500$)	

To compare the results against estimations based on the EC5 approach, a ratio β was again introduced, representing the EC5 estimation, i.e., Equation (10), divided by the experimentally found mean load-bearing capacity. The EC5 estimation (Equation (10)) was performed using either the mean embedment strength found from tests, $f_{h,0,m}$, or using the estimated embedment strength $f_{h,0,EC5}$, i.e., Equation (9). The resulting values of β are presented in Table 5.

3.3. Perpendicular to the Grain Loading

Load–displacement responses for loading perpendicular to the grain are shown in Figure 9, and the evaluated ductility (D_f) is presented in Table 6.

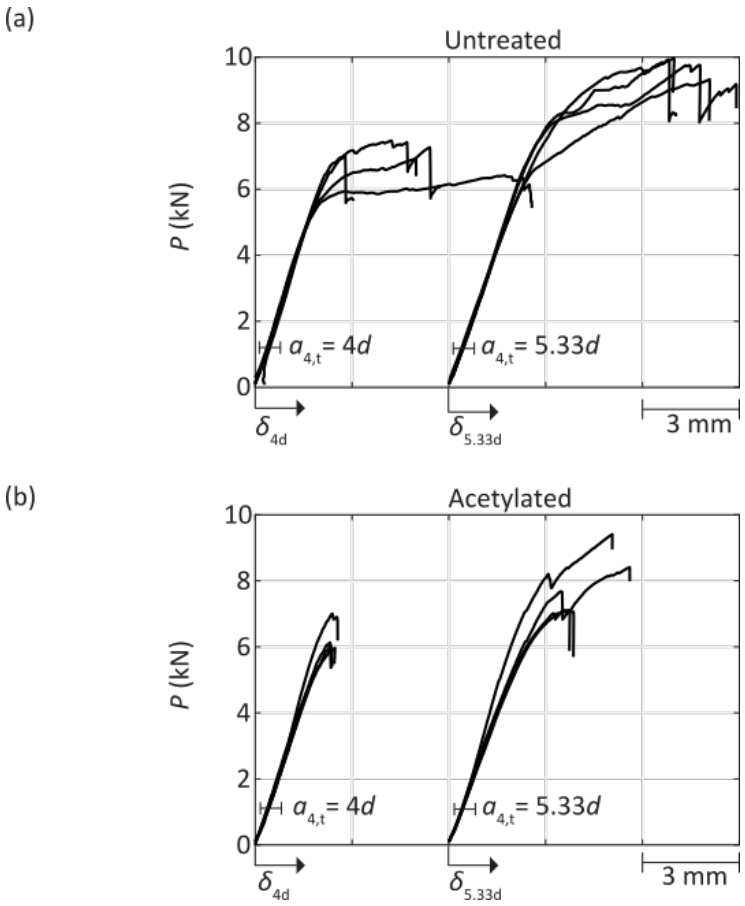


Figure 9. Load–displacement responses observed for connections loaded perpendicular to the grain for untreated (**a**) and acetylated wood (**b**) with varying edge distances $a_{4,t}$ (d = 12 mm).

Table 6. Ductility, D_f, evaluated for dowel-type connections loaded perpendicular to the grain.

$a_{4,t}$	4d	5.33d
Untreated	3.1	3.0
Acetylated	1.3	2.0

For untreated wood, both edge distances yielded responses with low ductility ($D_f \approx 3$), and the failure modes were attributed to splitting along the grain (Figure 10a). For acetylated wood, the minimum edge distance according to EC5, $a_{4,t} = 4d$, resulted in clearly brittle responses ($D_f = 1.3$), caused by splitting (Figure 10b). Increasing the edge distance to 5.33d increased the ductility ratio ($D_f = 2$), but the failure modes were still considered brittle.



Figure 10. Typical failure modes observed for untreated (**a**) and acetylated wood (**b**).

Mean values of the load-bearing capacity for dowel-type connections loaded perpendicular to the grain, $F_{90,m}$, are presented in Table 7. Statistical significance of difference in mean values were evaluated using Student's *t*-test, assuming unequal variance and significance at level 0.05. Comparing untreated and acetylated wood, a small although not statistically significant difference in load-bearing capacity was identified for the recommended minimum edge distance $a_{4,t} = 4d$. However, for an increased edge distance, acetylated wood demonstrated a significantly lower capacity compared to the untreated wood. To evaluate the load-bearing capacity against the EC5 approach, a ratio β was again introduced, indicating the relation between the estimated values according to the EC5 approach, i.e., Equation (10) using either the observed embedment strength $f_{h,90,m}$ or the estimated embedment $f_{h,90,EC5}$ (Table 3), and the experimentally found mean load-bearing capacity. It was found that the capacity calculated according to EC5 gave an over-estimation in all cases except for one: connections made from untreated wood with an increased edge distance, $a_{4,t} = 5.33d$.

Table 7. Mean load-bearing capacity for connections loaded perpendicular to the grain, $F_{90,m}$ in (kN). The ratio β represents the EC5 estimation (Equation (10) based on either the mean or the EC5 estimate of the embedment strength) divided by the mean load-bearing capacity. The difference in load-bearing capacity between untreated and acetylated wood $\Delta F_{90,m}$ is marked (*) if significant using Student's *t*-test assuming unequal variance ($p < 0.05$).

$a_{4,t}$		$4d$	$5.33d$
Untreated	$F_{90,m}$	6.97	9.75
	β_m	1.2	0.89
	β_{EC5}	1.2	0.84
Acetylated	$F_{90,m}$	6.29	8.01
	β_m	1.5	1.2
	β_{EC5}	1.3	1.1
$\Delta F_{90,m}$		−10%	−18% * ($p = 0.0484$)

4. Discussion

This study has focused on acetylated wood and the increased brittleness obtained due to the acetylation. However, it should be emphasised that the conclusions drawn in regard to the influence of material brittleness on the mechanical behaviour of dowel-type joints can be generalised (see Equation (8) and the related discussion in Section 2.3.3). Consequently, the results and the below discussion are relevant for situations that involve altered material brittleness in general, not only for acetylated wood. Examples of such situations include other modification techniques and other wood species than spruce/pine.

In regard to the embedment strength for loading perpendicular to the grain, EC5-based estimates using mean density values provided strengths 5–11% lower than the mean strength found from the tests (see Table 3). However, for loading parallel to the grain of acetylated wood, the EC5 approach severely underestimated (24%) the embedment strength, indicating that the parameters $f_{h,0,k}$ and k_{90} (see Equation (9)) should be adapted. Thus, the current EC5 approach seems to be (very much) on the safe side and, consequently, if a brittle failure mode is acceptable, it could also be used for acetylated Scots pine (in loading parallel to the grain). It should be mentioned that for the embedment tests with loading parallel to the grain, most samples failed due to splitting prior to reaching a displacement of 5 mm, indicating that the embedment strength has in fact been underestimated.

For the connection tests with loading parallel to the grain, the predictions based on the estimated embedment strength (from measured density) gave conservative values of the load-bearing capacity (see Table 5). However, the predictions based on the measured embedment strength were non-conservative for the acetylated wood, and premature brittle failures occurred. The conclusion is that the increased embedment strength of acetylated wood cannot be fully utilised, and the load-bearing capacity will be limited by brittle failure modes. To utilize the increased embedment strength of dowel-type connections made from acetylated wood while still ensuring ductile failures, reinforcement of the joints would be needed. Such reinforcement can be in the form of self-tapping screws inserted perpendicular to the grain or by applying surface reinforcements using glued-on wood plates using nail plates or punched metal plate fasteners (see, e.g., [29]). Alternatively, if only a ductile failure is sought and a limited capacity can be accepted, yielding of dowels should be promoted by using slender dowels and/or dowels of a lower steel grade.

In this study, the load-bearing capacity of connections loaded perpendicular to the grain was clearly limited by brittle failure modes rather than embedment strength. As presented in Equations (1)–(3), the failure of dowel-type joints loaded perpendicular to the grain is governed by the fracture characteristics of the material. Since previous studies [11,17–19] have demonstrated a decreased fracture energy for acetylated wood, an increased brittleness of mechanical joints made from such wood can be expected. Regarding the effect of acetylation on the shear force capacity, a simple estimate can be made. Considering Equation (3), assuming that all other characteristics remain unaltered by the chemical modification, a reduction in the fracture energy by 50%, as seen in [11,18], would result in a reduction in load-bearing capacity of approximately 30%.

In Figure 11, the mean load-bearing capacity for untreated and acetylated wood is presented along with estimates based on Equation (10) for embedment failure, and Equation (2) for splitting. The predicted capacity in splitting for a reduced fracture energy (−50%), resulting in a reduced splitting capacity of 30%, is given. As can be observed for the recommended edge distance ($a_{4,t} = 4d$), EC5 severely overestimates the splitting capacity for both untreated and acetylated wood (note that the EC5 estimates refer to characteristic values and the test results refer to mean values). This insufficiency in the current design provisions of EC5 for loading perpendicular to the grain, both for untreated and for acetylated wood, has been indicated in previous studies [30–32]. Further, the results indicate that a decreased splitting capacity should be considered for acetylated wood as compared to untreated wood.

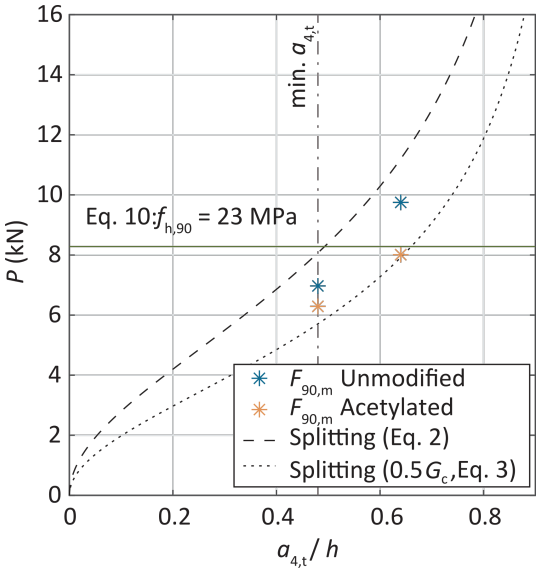


Figure 11. Mean load-bearing capacity of dowel-type connections loaded perpendicular to the grain along with EC5 estimates (characteristic values) based on embedment strength and splitting capacity.

5. Further Research

To develop further understanding of the brittleness of dowel-type connections in general, studies should be extended to include connections with multiple fasteners made from material more brittle than the softwoods referred to in EC5. The study of multiple fastener joints will give information about possible minimum distances between fasteners. Studies could be performed on acetylated wood or other wood species than the commonly used softwoods. In regard to the specific influence of the acetylation process, it is also important to remember that other design parameters may be affected. As an example, studies on Accoya® wood [33] have shown a decreased impact on strength values at conditions corresponding to Service Class 3, indicating that values for the modification factor k_{mod} for acetylated wood should be given consideration.

6. Concluding Remarks

Based on findings from this study, the following can be concluded:

- Compared to untreated wood, acetylated Scots pine demonstrated a significantly increased embedment strength parallel to the grain, while no difference for embedment strength could be found for perpendicular to the grain loading.
- For acetylated wood, using the measured density in combination with the EC5 approach provided reasonably conservative estimations of the embedment strength perpendicular to the grain (−11%). However, the embedment strength parallel to the grain was severely underestimated (−24%).
- For dowel-type connections loaded parallel to the grain, acetylated wood demonstrated an increased load-bearing capacity compared to untreated wood.
- Using the EC5 approach, a conservative estimation of the load-bearing capacity for dowel-type connections parallel to the grain was obtained. However, connections made from acetylated wood failed in a brittle manner. To achieve ductile responses but at the same time utilize the full potential of increased embedment strength, reinforced joints are recommended.
- The load-bearing capacity of dowel-type connections loaded perpendicular to the grain was lower for acetylated wood compared to untreated wood.

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