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Pure-Timber Connections with Beech, Birch, and Laminated Densified Wooden Dowels: Experimental and Analytical Investigations

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ABSTRACT: The use of wooden dowels has been expanding in recent years within timber engineering, particularly in the development of adhesive-free engineered wood products. Adhesive-free timber structures offer advantages such as enhanced recyclability, improved reusability, and a reduced environmental impact. Typically, metal fasteners, e.g., screws, dowels, or the like, are employed in timber engineering applications, mainly due to issues such as mechanical performance, ease of application, and economy. Despite the proven performance and widespread adoption of metal connectors, the timber industry increasingly considers wood-based connectors, such as wood dowels (also referred to as ”pegs”), eco-friendly alternatives. This study aims to evaluate predictive models for the capacity of connections with wooden dowels. The authors tested glulam-to-plywood connections with fasteners made of either birch, beech, or laminated densified wood dowels. Additionally, reference tests were performed using conventional self-tapping screw connections, and the results were compared. Supplementary tests were also conducted on the dowels to estimate their bending, shear, and embedment strengths. Selected predictive capacity models are compared, including that in the new Eurocode 5 proposal.

KEYWORDS: Wooden dowels, experimental testing, timber connections, mechanics-based model, failure mode.

1 – INTRODUCTION

Chemical adhesives and metallic fasteners have dominated connections in timber engineering. The former is predominantly employed for bonding wood layers when producing engineered wood products, while the latter is mainly adopted to join structural elements [1,2].

The extensive use of adhesives has raised concerns about recyclability, reusability, and environmental impact. Although adhesives comprise less than 2% of the total mass of CLT or GLT panels, they account for almost one-third of the product’s overall environmental footprint [3]. Under fire conditions, adhesives like phenol formaldehyde (PF) or polyurethane (PUR) pose risks for delamination [4]. Besides, petroleum-based adhesives contribute to releasing Volatile Organic Compounds (VOCs) and formaldehyde [5]. Given this, wooden dowels possess the potential to be a promising bio-based alternative to adhesives in the manufacture of engineered wood products.

Metal fasteners have been commonly adopted due to their promising load-bearing capacity and ductility [6]. Meanwhile, the industry is actively exploring the potential of wood-based connectors, i.e., wooden dowels and nails, as eco-friendly alternatives. The motivations are mainly that wood-based connectors are more compatible with the timber substrate, facilitating disassembly and improving recyclability and reusability [7].

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Johansen's model [8] predicts the capacity of connections with metallic fasteners by examining the yielding in metallic fasteners or the compression failure of wood fibres. By applying equilibrium and plasticity theories, the capacity estimation is under various failure conditions for both single and double-shear plane connections, highlighting four primary failure modes: wood substrate embedment failures (mode I and mode II, single shear connections); formation of one plastic hinge (mode III) or two plastic hinges (mode IV) within the metal fastener [9].

Unlike steel dowels, wooden dowels, with their mechanical properties compatible with substrate timber, exhibit unique failure modes requiring dedicated mathematical formulations. As initially noted by [10], a recurring yielding failure 'Mode V' for wooden dowels results from a combination of bending and shear forces. 'Mode V' is an additional failure mechanism beyond Johansen's theory, as it accounts for the combined effects of bending, shear, and compression perpendicular to the grain [10,11].

Several studies have pointed out the limitations of applying Johansen's model (EYM) to timber pegged joints without adjustments, especially considering the need to modify the embedding strength formula to account for the densities of the base material and the wooden dowel. Ceraldi et al. [12] proposed a simplified but conservative approach that requires the experimental determination of the radial confined compressive strength of the wooden dowel. The bending yield moment of the wooden dowel can then be calculated by adapting the theoretical mode in Eurocode 5 for steel bolts [9], substituting the tensile strength value with the axial compressive strength of the timber peg [13]. Sandoli et al. [14] suggest that the embedment strength formulas incorporating the densities of both the wooden dowel and the base material are more suitable than those used for steel fasteners (suggested in Eurocode 5 [9]).

Nevertheless, there is still a lack of studies that use mechanics-based, rather than heuristic, models specifically focused on wooden dowels. This study includes systematic experiments on glulam-plywood connections with wooden dowels (beech, birch, and laminated wooden dowels). The embedment (into glulam substrate), bending, and shear strength values of individual wooden dowels were characterized further to confirm the role of wooden dowel density values.

Moreover, the measured connection stiffness and capacity values were summarized, and the accuracy of existing capacity models (as proposed by Miller et al. [11] and prEN1995-1-1 [15]) was evaluated when predicting failure modes associated with failure mode V.

2 – MATERIALS AND METHODS

2.1 Utilized timber and other materials

The utilized timber elements are combined glued laminated timber GL30c made of spruce, characterized by EN 14080 [16]. The outermost laminations have a strength class of T22, while the inner laminations are T15 class. These timber elements are 605 mm long, with a section height of 180 mm and a width of 90 mm.

The average density of GL30c is 430 kg/m^3 (according to), and the laminations' thickness is 45 mm. The gusset plates are made of birch plywood, consisting of 1.4 mm thick layers with an average density of 680 kg/m^3. They are 660 mm long and have the same depth as the glulam elements.

Four connection configurations were tested, mainly differing in the species of dowels. Table 1 summarizes the detailed descriptions of all tested groups.

Table 1: Summary of all tested connection configurations.

Notation	Fastener	Num of shear plane	Num of fasteners	Test replicas
BE-D	Beech	4	2	1
BI-D	Birch	4	2	4
LDW-D	Laminated densified	4	2	5
S-S	Steel screws	4	2	5

All utilized wood dowels were 300 mm long with a nominal diameter of 20 mm. The dowel's diameter was chosen as the most practical standard size that can be used in timber structures, achieving comparable mechanical properties to steel screws with diameters of 8 to 10 mm.

The beech and birch dowels were manufactured from solid lumber by the company Aanesland® and have mean densities of 668 and 608 kg/m^3, respectively. The utilized LDW dowels, Lignostone®, are laminated, densified wood products made from red beech. The beech veneers are combined with high temperatures and bonded by a curable synthetic resin.

The mechanical properties declared by Röchling® are summarized in Table 2.

Table 2: Properties of LDW dowels: Density (ρ), bending strength (f_b), bending modulus (E_b), compressive strength parallel (f_{c0}) and perpendicular to the grain (f_{c90}), tensile strength parallel to the grain (f_{t0}), and moisture content (MC).

ρ (kg/m^3)	f_b (N/mm^2)	E_b (N/mm^2)	f_{c0} (N/mm^2)	f_{c90} (N/mm^2)	f_b (N/mm^2)	MC (%)
1350	200	16000	90	120	170	5

The fully threaded self-tapping screws used are VGZ 9× 280, manufactured by Rothoblaas®. These screws are 280 mm long with a nominal diameter of 9 mm.

2.2 Test setup and loading procedure

The specimens were tested to failure using a ZwickRoell Z1200 Universal Testing Machine with a capacity of 1200 kN (Fig. 1). All minimum spacings, edge, and end distances for laterally loaded dowel-type fasteners comply with the limits specified by prEN1995-1-1 [15]. Please refer to Figures 1a and 1b for the detailed spacing values.

The slip between the gusset plates and the glulam members (u_1 and u_3), as well as the relative displacement between the connected members (u_2 and u_4), was measured using LVDTs (Fig. 1b). It is worth noting that only the displacement from the machine piston was measured for the prototype specimen with beech dowels (BE-D).

The displacement u represents the slip of each connection, which is defined as the average relative displacement between the glulam member and the gusset plate:

$$u = (u_1 + u_2/2 + u_3 + u_4/2) / 4 \quad (1)$$

The loading procedure adopted in this study followed the guidelines given in EN 26891 [17], which requires an estimated maximum load F_{est} as a pre-inputted value. The maximum load for each configuration was calculated via the analytical model, which will be described later in Sections 3.1 and 3.2.

The loading protocol includes five phases under force control and a final phase under displacement control: i) a partial load up to $0.4F_{est}$, ii) a 30-second hold, iii) partial unloading to $0.1F_{est}$, iv) another 30-second hold, v) re-loading to 70% of the estimated maximum load, vi) displacement-controlled loading until failure occurs. The loading rate is selected to ensure that the final failure happens within a total test duration of 10 to 15 minutes.

The initial slip modulus, which indicates the stiffness of the connection during the first loading phase, is defined as:

$$k_i = 0.4F_{est} / v_{04} \quad (2)$$

The slip modulus measures the stiffness of the connection in the first loading phase, neglecting the initial slip, and it is determined as follows:

$$k_s = (0.4F_{est} - 0.1F_{est}) / (v_{04} - v_{01}) \quad (3)$$

where v_{04} and v_{01} are the relative slips in the loading phase, respectively, corresponding to $0.4F_{est}$ and $0.1F_{est}$.

The stiffness during the reloading phase is defined as:

$$k_{s,r} = (0.4F_{est} - 0.1F_{max}) / (v_{24} - v_{21}) \quad (4)$$

where v_{24} and v_{21} are the relative slips in the re-loading phase, respectively, corresponding to $0.4F_{est}$ and $0.1F_{est}$.

The ultimate slip modulus is defined in the EC 5 [9] as:

$$k_u = 2/3 \cdot k_s \quad (5)$$

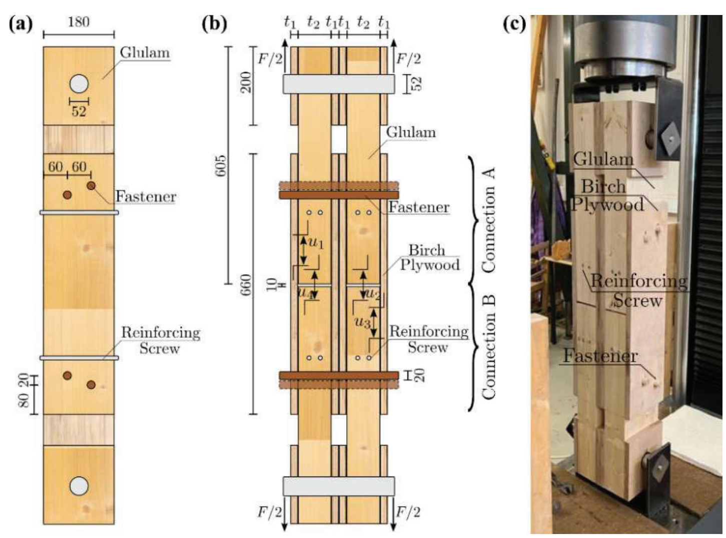

Figure 1. a) Side view and b) front view of a schematic setup drawing, and c) picture of a test specimen erected on the test machines.

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However, the commonly used reduction factor of 2/3 may not accurately capture the genuine behavior of different joint types, potentially resulting in an inaccurate estimation of ultimate stiffness [18]. Considering the actual non-linear load-displacement behavior of connections at the ultimate limit state, a different approach to estimating the effective stiffness near failure, based on experimental data, was proposed in [19] and subsequently applied here:

$$k_{u,p} = (F_{max} - 0.6F_{max}) / (v_u - v_{26}) \tag{6}$$

where v_u and v_{26} are the relative slip in the reloading phase corresponding to F_{max} and $0.6F_{max}$.

Besides, ductility values were also extracted from measured load-slip curves. The ductility ratio is defined as the ratio between ultimate slip u_u and yield slip u_y:

$$D = u_u / u_y \tag{7}$$

The yield slip is determined by the intersection of the two projected lines, according to the guidelines in EN 12512 [20]. The definition is schematically presented in Figure 2.

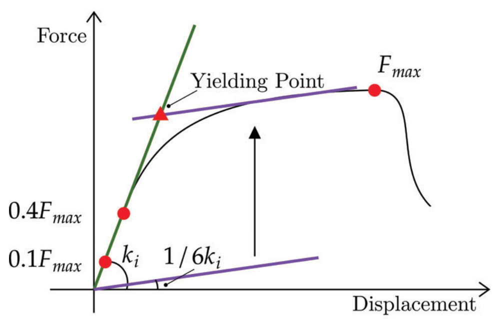

Figure 2. Definition of yield point on force-displacement curves.

In Figure 2, the green line is the secant line passing through the points on the load-slip curve corresponding to $0.1F_{max}$ and the point on the load-slip curve corresponding to $0.4F_{max}$. The purple line is the tangent line to the experimental curve obtained by translating a line upward with a slope equal to 1/6 of the green line's slope.

The ultimate slip u_u as in EN 12512 [20] is taken as the minimum of 30 mm, and the slip corresponds to a 20% load reduction concerning the maximum force achieved during the test. Since none of the tested connections reached 30 mm, u_u is located at the beginning of the softening branch in the analyzed cases.

2.3 Supplementary tests on embedment, bending, and shear strength of wooden dowels

A testing campaign on the material properties of birch and densified wood dowels was conducted at the Norwegian University of Life Sciences in Ås, Norway, to characterize the fasteners' embedment, bending, and shear strength.

A half-hole embedment configuration was adopted, as in Figure 2. Steel, birch, and LDW dowels were tested on plywood and glulam, both parallel and perpendicular to the grain. All specimens are summarized in Table 3.

Table 3: Summary of all embedment test configurations.

Notation	Substrate	Dowel	Angle (°)	d (mm)	t (mm)
EMB-GL0-S	Glulam	Steel	0	20	90
EMB-GL90-S	Glulam	Steel	90	20	90
EMB-PLY-S	Plywood	Steel		20	61
EMB-GL0-BI	Glulam	Birch	0	20	90
EMB-GL90-BI	Glulam	Birch	90	20	90
EMB-PLY-BI	Plywood	Birch		20	61
EMB-GL0-LDW	Glulam	LDW	0	20	90
EMB-GL90-LDW	Glulam	LDW	90	20	90
EMB-PLY-LDW	Plywood	LDW		20	61

The strength and stiffness values are determined according to the guidelines in EN 383 [21]. The initial foundation modulus is defined as:

$$K_i = 0.4 \cdot f_{h.est} / u_i \tag{8}$$

where u_i is the slip corresponding to 40% of the estimated maximum load on the first loading branch, and $f_{h.est}$ is the estimated embedment strength.

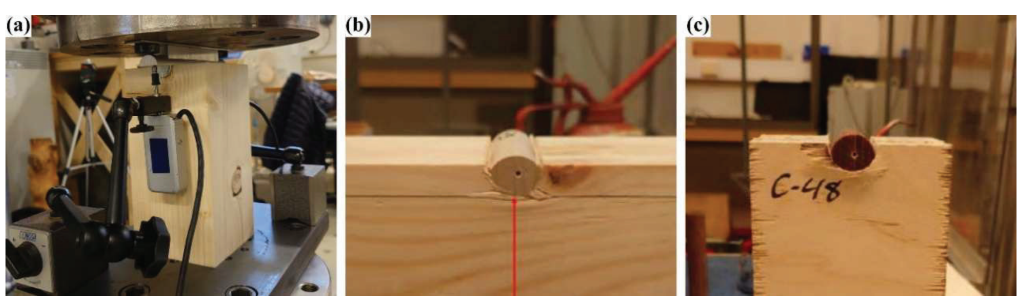

Figure 3. Illustration on the embedment test setup of a) steel dowel (into glulam), b) birch dowel (into glulam), and c) laminated densified dowel (into plywood).

The strength and stiffness are determined according to EN 383 [21]. The initial foundation modulus is defined as:

$$K_s = 0.4 \cdot f_{h.est} \,/\, u_{i,mod} \quad (9)$$

where $u_{i,mod}$ is the modified initial deformation calculated as 4/3 of the difference between the slip corresponding to 40% of the estimated maximum load and the slip corresponding to 10% of the estimated maximum load on the first loading branch, and $f_{h.est}$ is the estimated embedment strength.

The embedment strength is defined as:

$$f_h = F_{max} \,/\, dt \quad (10)$$

where F_{max} is the maximum load reached before the attainment of 5 mm of displacement excluding the test apparatus deformation, d is the dowel diameter, and t is embedment thickness.

Four-point bending tests were performed to measure the shear and bending properties of the birch and laminated densified wood dowels, as presented in Figure 4. The tests were performed following guidelines in EN 408 [22] .

By adopting different positions of load application points, either shear failure or bending failure were achieved on test specimens, which are summarized in Table 4. Ten replicates for each test configuration were conducted.

Table 4: Summary of all bending and shear test configurations: density (ρ), dowel diameter (d), dowel length (l), support-load application point distance (a), distance between load application points (b), and edge distance (c).

Notation	Dowel	Test type	ρ (kg/mm^3)	d (mm)	a (mm)	b (mm)	c (mm)
BI-D-S	Birch	Shear	618	20	70	325	17.5
BI-D-B	Birch	Bending	599	20	155	155	17.5
EMB-D-S	LDW	Shear	1336	20	70	325	17.5
LDW-D-B	LDW	Bending	1333	20	155	155	17.5

The bending strength has been assumed as the bending stress at the outermost fibers, following the Navier formula:

$$f_m = \frac{M_u}{I} \cdot \frac{d}{2} \quad (11)$$

where M_u is the bending moment at the middle of the dowel at failure, d is the dowel diameter and I is the second moment of inertia.

The shear stress at dowel failure is calculated as:

$$\tau_v = \frac{4}{3} \cdot \frac{T_u}{A} \quad (12)$$

where T_u is the shear force at failure in the later portion of the dowel, and A is the sectional area.

3 – Analytical prediction models

3.1 Capacity model by Miller et al.

According to Miller et al. [23], failure mode V involves multiple longitudinal shear fractures distributed across the dowel's cross-section. Thin bundles of intact longitudinal fibers remain between the fractures, which are flexibly kinked. Consequently, the yield capacity of the connection is determined by applying an average stress value to the dowel's cross-sectional area. Miller et al. also refer to this as the "effective peg shear yield mode".

Based on three-dimensional non-linear numerical simulations, Miller et al. [11] proposed the following regression model to estimate the average allowable shear stress, f_v, in the wooden dowel:

$$f_v = 33.44 \cdot G_d \cdot G_m^{0.75} \quad (13)$$

where f_v is the allowable shear stress in the dowel (in N/mm^2), $G_d = \rho_d/\rho_w$ is the dowel's specific gravity and $G_m = \rho_m/\rho_w$ is the substrate's specific gravity. Specifically, ρ_d, ρ_m and ρ_w are the dowel, embedment, and water mass densities, respectively.

The shear capacity of the connection is obtained simply by multiplying f_v with the shear cross-sectional area (A):

$$F_v = f_v \cdot A \quad (14)$$

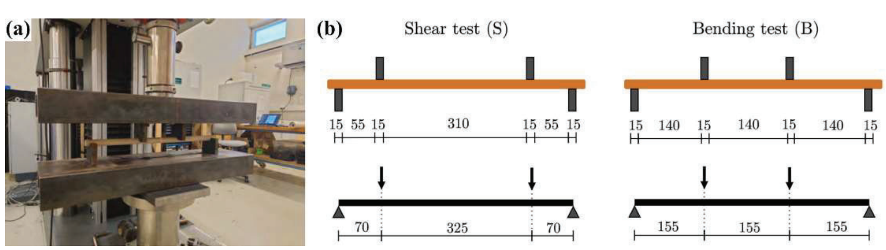

Figure 4. a) Test picture and b) schematic demonstration of the tests characterizing bending and shear properties of wooden dowels by adopting different positions of load application points.

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3.2 Capacity model in Eurocode 5 proposal

For timber-to-timber connections using wooden dowels, the characteristic dowel-effect part $F_{\mathrm{D,k}}$ per shear plane, is obtained by modifying the Johansen equations:

$$F_{\mathrm{D,k}} = \min \begin{cases} f_{h,1,k}\, t_{h1}\, d & (a) \\ f_{h,2,k}\, t_{h2}\, d & (b) \\ \frac{f_{h,1,k}\, t_{h1}\, d}{1+\beta}\left[\sqrt{\beta + 2\,\beta^2\left[1+\frac{t_{h2}}{t_{h1}}+\left(\frac{t_{h2}}{t_{h1}}\right)^2\right]+\beta^3\left(\frac{t_{h2}}{t_{h1}}\right)^2} - \beta\left(1+\frac{t_{h2}}{t_{h1}}\right)\right] & (c) \\ \frac{f_{h,1,k}\, t_{h1}\, d}{2+\beta}\left[\sqrt{2\,\beta\,(1+\beta)+\frac{4\,\beta\,(2+\beta)\,M_{u,k}}{f_{h,1,k}\, d\, t_{h1}^2}} - \beta\right] & (d) \\ \frac{f_{h,1,k}\, t_{h2}\, d}{1+2\,\beta}\left[\sqrt{2\,\beta^2\,(1+\beta)+\frac{4\,\beta\,(1+2\,\beta)\,M_{u,k}}{f_{h,1,k}\, d\, t_{h2}^2}} - \beta\right] & (e) \\ \sqrt{\frac{2\,\beta}{1+\beta}}\,\sqrt{2\,M_{u,k}\, f_{h,1,k}\, d} & (f) \end{cases}$$

where $\beta = \frac{f_{h,2,k}}{f_{h,1,k}}$, $f_{h,1,k}$ and $f_{h,2,k}$ are the characteristic embedment strength of members 1 and 2, respectively. $t_{h,1}$ and $t_{h,2}$ are the embedment thickness of members 1 and 2. $M_{\mathrm{u,k}}$ is the characteristic ultimate moment given in Equation 15, and d is the fastener diameter.

According to prEN1995-1-1:2024 [15], the characteristic ultimate bending moment for wooden dowels, with a diameter varying from 12 mm to 30 mm, is calculated as:

$$M_{\mathrm{u,k}} = 0.75 \cdot \frac{\pi}{32} \cdot f_{m,k} \cdot d^3 \qquad (15)$$

where $f_{m,k}$ is the characteristic bending strength of the wooden dowel.

The characteristic embedment strength $f_{\mathrm{h,k}}$ for wooden dowels in Structural lumber (SL), parallel laminated timber (PLT), and wide faces of cross-layered timber (CLT) is according to prEN1995-1-1:2024 [15].

$$f_{h,k} = 10^{-4} \rho_{dowel,k} \cdot \rho_k \cdot \frac{1.1(1-0.01d)}{(3.4-0.045d)sin\alpha^2 + cos\alpha^2} \qquad (16)$$

where $\rho_{dowel,k}$ and ρ_k are the characteristic densities of the wooden dowel and the embedment substrate, and d is the dowel and α is the grain direction.

3 – RESULTS AND DISCUSSIONS

3.1 CONNECTION TESTS

The force-slip curves of all tested connections in this study are presented in Figure 5.

The curves depict a nearly bilinear response for all connections with wooden dowels, with an initial phase of uniform stiffness followed by a plateau and failure. This behavior differs from the screw connections, where virtually there is no plateau. Instead, screw connections exhibit a non-linear response with progressively decreasing stiffness. The screw connections also provide more significant strength reserves and ductility than the wooden dowel connections. For instance, at 15 mm of slip, the screw connections reached a similar capacity to the LDW-D series at approximately 80 kN.

Inspecting the force-displacement curves among the wooden dowel connections, the ones with birch dowels exhibit the most ductile response, followed by beech and LDW. Moreover, while beech and birch dowel connections possess similar capacities (around 40 kN), the LDW has nearly double that value. This suggests that while the lamination and densification process enhances wood's resistance, it also results in higher brittleness.

The failure modes shown in Figures 5e and 5f align with two limiting behaviors noted by Sandoli et al. [14]: (i) a strong wooden dowel within a weak base material, and (ii) a weak wooden dowel within a strong base material.

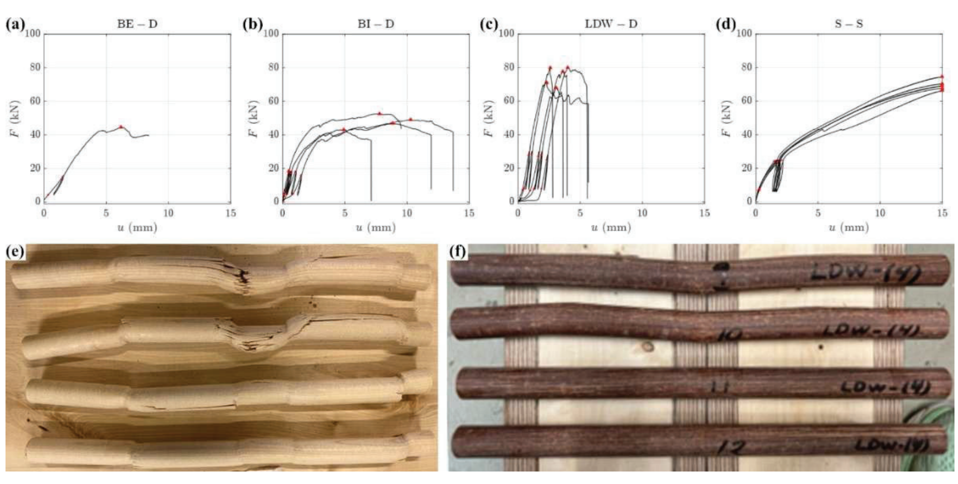

Figure 5. Experimental force (F) vs. connection slip (u) curves for connections with a) beech dowels, b) birch dowels, c) laminated densified wooden dowels, and d) steel screws. Failure modes of e) birch dowels and f) LDW dowels.

The 'conventional' failure load (R_v) has been evaluated according to the standard by considering the part of the curve up to 15 mm of relative slip. The absolute maximum loads have also been calculated ($R_{v,a}$). Table 5 shows the averaged conventional failure load R_v, the associated ultimate displacement u_v, the absolute failure load $R_{v,a}$, and the associated displacement $u_{v,a}$.

Table 5:Avergae failure loads per configuration: conventional (R_v) and absolute ($R_{v,a}$) and corresponding slip of the tested connections.

Configuration	R_v (kN)	u_v (mm)	$R_{v,a}$ (kN)	$u_{v,a}$ (mm)
BE-D	44.6	6.2	44.6	6.2
BI-D	47.9 (7%)	8.0 (25%)	43.1 (7%)	4.9 (25%)
LDW-D	75.3 (7%)	3.1 (20%)	75.3 (7%)	33.1 (20%)
S-S	69.7 (4%)	15.0 (0%)	72.2 (5%)	19.6 (11%)

The laminated densified wood dowels configuration exhibited slightly higher conventional ultimate strength than the screw configuration. Even including the part of the curve beyond 15 mm of slip for the screws, the maximum force achieved during the test of LDW-D configuration is higher than that of S-S.

Although only one test was performed on connection with beech dowels, results indicate that beech and birch dowels connection are characterized by similar ultimate strength. Their strength values are respectively 31 to 38% lower than steel screw configuration. The ultimate displacement of configurations with dowels resulted to be 47% to 84% lower than that of the screw configuration. The laminated densified wood dowel configuration is characterized by the lowest ultimate displacement, which equals 3.1 mm.

Besides, the stiffness values of all connection specimens are summarized in Table 6.

Table 6:Experimentally determined slip values per connection: initial (k_i), in-service (k_s), re-loading ($k_{s,r}$), conventional ultimate (k_u), and alternative ultimate ($k_{u,p}$).

Configuration	k_i (kN/mm)	k_s (kN/mm)	$k_{s,r}$ (kN/mm)	k_u (kN/mm)	$k_{u,p}$ (kN/mm)
BE-D	10.1	9.2	13.4	6.1	4.9
BI-D	25.2 (44%)	25.1 (34%)	36.5 (32%)	16.1 (35%)	3.2 (30%)
LDW-D	20.6 (40%)	36.9 (11%)	64.4 (8%)	24.6 (11%)	26.5 (9%)
S-S	14.5 (10%)	11.9 (9%)	27.1 (15%)	7.9 (9%)	2.8 (5%)

Among the four configurations, the connections with LDW dowels were the stiffest. Compared to the screw connection, they exhibited a 42% higher initial slip modulus, a 209% higher slip modulus, and an 859% higher 'alternative' ultimate slip modulus, according to [24,25].

The connections with birch dowels showed slightly higher initial stiffness than those with LDW dowels but significantly lower in-service and ultimate stiffness. The differences in terms of initial slip modulus, slip modulus, and proposed ultimate slip modulus relative to the screw configuration were 74%, 111%, and 16%, respectively. Notably, except for the LDW configuration, there is a substantial difference between the conventional ultimate stiffness (k_u) and the ultimate stiffness calculated using the alternative definition ($k_{u,p}$), as in Table 6).

In three out of four configurations, the stiffness reduction between in-service and ultimate condition is greater than 1/3. Thus, the conventional definition of ultimate stiffness is suitable only for the LDW dowel connection, which fails without significantly reducing stiffness.

Moreover, the ductility ratios of all investigated connections are summarized in Table 7.

Table 7:Yield slip (u_y), ultimate slip (u_u), and ductility ratios (D) of all tested connections.

Configuration	u_y (kN)	u_u (mm)	*D*
BE-D	4.4	7.3	1.6
BI-D	1.6 (42%)	10.6 (24%)	7.3 (23%)
LDW-D	2.7 (21%)	4.3 (26%)	1.6 (25%)
S-S	3.6 (12%)	24.6 (17%)	6.9 (17%)

As a result, connections with birch dowels showed ductility values similar to the screw ones (Table 7), while beech and laminated densified wood dowels connections are characterized by very low ductility.

3.2 Embedment properties

The embedment stiffness data are summarized in Table 8.

Table 8: Summary of all embedment test configurations.

Notation	K_i (N/mm^3)	**CoV**	K_s (N/mm^3)	**CoV**
EMB-GL0-S	18.5	9%	23.8	6%
EMB-GL90-S	5.6	7%	5.9	3%
EMB-PLY-S	14.6	26%	26.1	11%
EMB-GL0-BI	3.5	19%	3.0	22%
EMB-GL90-BI	4.5	17%	4.3	21%
EMB-PLY-BI	4.0	12%	3.6	11%
EMB-GL0-LDW	15.6	16%	21.0	17%
EMB-GL90-LDW	5.6	19%	5.7	19%
EMB-PLY-LDW	23.4	13%	30.3	13%

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Plywood possesses significantly higher foundation modulus and embedding strength than glulam loaded parallel to the grain. The most ductile behavior is obtained when loading the glulam perpendicular to the grain. However, the lowest stiffness and strengths are associated with this configuration.

Steel dowels in the EMB-GL0-S configuration also exhibit a relatively high initial modulus, while birch dowels have the lowest stiffness in most configurations, especially in EMB-GL0-BI. The LDW dowels perform similarly to steel dowels in the GL0 configuration, showing comparable stiffness with steel, especially in EMB-GL0-LDW and EMB-GL0-S.

The measured embedment strength values are also summarized in Table 9. The estimated embedment strength values based on Equation 16 are also presented.

Table 9: Summary of conventional embedment strength f_h and corresponding displacement $f_{h,max}$; displacement corresponding to the maximum embedment strength $u(f_{h,max})$; Eurocode 5 prediction value $f_{h,EC5}$ and difference with respect to the experimental values $D_{\%}$.

Notation	f_h (MPa)	$u(f_h)$ (mm)	$f_{h,max}$ (MPa)	$u(f_{h,max})$ (mm)	$f_{h,EC5}$ (MPa)	$D_{\%}$ (%)
EMB-GL0-S	28.9 (10%)	2.3 (9%)	28.9 (10%)	2.3 (9%)	32.8	14%
EMB-GL90-S	14.8 (9%)	4.8 (6%)	15.5 (10%)	6.2 (3%)	13.1	-11%
EMB-PLY-S	55.1 (3%)	5.0 (0%)	58.0 (1%)	6.7 (6%)	49.6	-10%
EMB-GL0-BI	17.8 (8%)	5.0 (0%)	31.3 (5%)	7.9 (10%)	25.7	45%
EMB-GL90-BI	12.6 (19%)	5.0 (2%)	16.3 (15%)	8.9 (10%)	10.3	-19%
EMB-PLY-BI	20.0 (9%)	5.0 (0%)	42.8 (4%)	8.2 (10%)	38.9	94%
EMB-GL0-LDW	29.9 (4%)	3.3 (15%)	29.9 (4%)	3.3 (15%)	49.2	65%
EMB-GL90-LDW	16.8 (29%)	5.0 (0%)	17.6 (28%)	6.0 (8%)	19.7	17%
EMB-PLY-LDW	55.5 (5%)	5.0 (0%)	57.6 (4%)	6.4 (11%)	74.4	34%

The EMB-PLY-S and EMB-PLY-LDW configurations returned the highest embedment strength values, with steel and LDW dowels performing almost equally well. Birch dowels, on the other hand, display lower embedment strength, especially in the GL0-BI and GL90-BI configurations. Birch dowels also exhibit higher displacements, indicating a more flexible connection. In contrast, LDW and steel dowels have lower displacements.

In conclusion, LDW dowels perform similarly to steel dowels. Especially when used with plywood, they demonstrate high stiffness, strength, and low displacement, making them a viable bio-based alternative. Birch dowels exhibit much lower stiffness and embedding strength than LDW and steel.

The Eurocode 5 model for predicting the embedment strength of connections with wooden dowels aligns well with experimental results for configurations testing the embedment capacity of glulam perpendicular to the grain. However, in other cases involving wooden dowels, the model overestimates the results by a margin between 34% and 94%. Besides, the Eurocode 5 model accurately predicts the embedment strength of steel dowels.

3.3 Bending (shear) properties

As mentioned in Section 2.3, Despite the two distinct test setups designed to induce bending and shear failures, all the dowels failed due to bending, with the damage localized to the central portion of the dowel.

The bending strength (f_m), the corresponding shear stress at failure (τ_v), with coefficients of variation (*CoV*) for each of the birch dowels (BI-D) and laminated densified wood dowels (LDW-D), are summarized in Table 10.

Table 10: Dowel shear and dowel bending tests results: bending strength (f_m) and shear stress at failure (τ_v).

Notation	f_m (MPa)	*CoV*	τ_v (MPa)	*CoV*
BI-D-S	143.2	15%	6.8	15%
BI-D-B	132.7	11%	2.9	11%
LDW-D-S	278.0	7%	13.2	7%
LDW-D-B	235.0	9%	5.1	9%

LDW dowels show a significantly higher bending strength compared to birch dowels. In the shear test configuration, LDW dowels reach a bending strength of 278 MPa, almost double that of birch dowels at 143.2 MPa. LDW dowels still exhibit a much higher value (235 MPa) than birch dowels (132.7 MPa) in the bending configuration.

The shear strength of LDW dowels is also significantly greater than that of birch dowels. LDW dowels show a shear strength of 13.2 MPa in the shear configuration, nearly double that of birch dowels (6.8 MPa). In the bending configuration, LDW dowels again outperform birch dowels (5.1 MPa versus 2.9 MPa).

3.4 MECHANICS-BASED MODEL FOR CAPACITY PREDICTION

Two literature models will be used for validation in this study: the one proposed by Miller et al. [11] and the one included in the new Eurocode 5 proposal [15].

It is worth noting that since the Eurocode 5 formulas predict the ultimate capacity, the prEC5 predictions have been compared to the ultimate shear capacity, as in Table 11. $R_{v,prEC5}$ were solely obtained from prEurocode 5 formulas, while $R_{v,prEC5}$ rely on experimental embedment and bending strength values of wooden fasteners.

Table 11: Comparison between experimental ultimate capacity per fastener per shear plane versus the predicted capacity based on modified Johansen's theory (Section 3.1).

Notation	$R_{v,exp}$ (kN)	$R_{v,prEC5}$ (kN)	Rel. Error (%)	$R_{v,prEC5,exp}$ (kN)	Rel. Error (%)
BI-D-1	6.56	8.43	28%	6.63	1%
BI-D-2	6.14	8.43	37%	6.63	8%
BI-D-3	5.86	8.43	44%	6.63	13%
BI-D-5	5.39	8.43	56%	6.63	23%
Mean	5.99	8.43	42%	6.63	11%
LDW-D-1	8.88	16.93	91%	13.08%	47
LDW-D-2	9.99	16.93	69%	13.08%	31
LDW-D-3	10.00	16.93	69%	13.08%	31
LDW-D-4	9.71	16.93	74%	13.08%	35
LDW-D-5	8.50	16.93	99%	13.08%	54
Mean	9.42	16.93	81%	13.08	39%

On average, the prEC5 model overestimates the capacity by 42% and 81% for birch and LDW connections, respectively. However, when using experimental embedment data instead of theoretical ones, the overestimation is reduced to 11% for birch and 39% for LDW connections. Therefore, the model is not conservative, and the error increases significantly when involving denser, stiffer, and more brittle dowels, e.g., LDW. This confirms the inadequacy of Johansen's model when describing connections with wooden dowels, as it does not account for the observed failure modes.

Conversely, in Table 12, the predictions from Miller's model are compared with the experimental yielding capacity since the model was specifically developed for yielding. It is worth mentioning that for LDW configurations, the yield capacity is considered the same as the ultimate ones due to their brittle failure manner.

Table 12: Comparison between experimental yield capacity per fastener per shear plane versus the predicted capacity based on Miller's model (Equations 13 and 14).

Notation	$R_{v,y,exp}$ (kN)	f_v Miller (MPa)	$R_{v,y,sim}$ Miller (kN)	Rel. Error (%)
BI-D-1	5.21	15.22	3.46	-34%
BI-D-2	4.55	15.22	3.46	-24%
BI-D-3	3.98	15.22	3.46	-13%
BI-D-5	4.56	15.22	3.46	-27%
Mean	4.61	15.22	3.46	-24%
LDW-D-1	8.88	33.43	7.61	-14%
LDW-D-2	9.99	33.43	7.61	-24%
LDW-D-3	10.00	33.43	7.61	-24%
LDW-D-4	9.71	33.43	7.61	-22%
LDW-D-5	8.50	33.43	7.61	-11%
Mean	9.42	33.43	7.61	-19%

Conversely, Miller's model returned conservative predictions, which tend to underestimate the yield capacity by 24% for birch and 19% for LDW dowel connections. The predictive performance of Miller's model appears significantly better than that of prEC5.

4 – CONCLUSIONS

This work concerns pure-timber connections adopting wooden dowels. Test series was conducted on glulam-plywood connections with three types of dowels: beech, birch, and laminated densified wood (LDW), with reference configurations tested with screws.

The force-slip curves for the tested connections revealed a bilinear response with an initial phase of nearly constant stiffness, followed by a plateau, then failure. Among the test configurations, birch ones showed the highest ductility, followed by beech and LDW, with ductility inversely proportional to dowel density. While beech and birch dowel connections achieved similar capacities of approximately 40 kN, LDW dowels reached nearly double this capacity, comparable to that of steel screws.

Supplementary tests provided embedment and bending strengths estimates as inputs for predictive capacity models. As a result, Miller's model underestimates capacity by 24% for birch and 19% for LDW dowel connections, indicating that although it considers the observed failure mode, it lacks accuracy in capacity prediction. The prEC5 model, on the other hand, substantially overestimates the capacity. Even when experimental embedment values are incorporated, the prEC5 model's estimates remain overly optimistic, overestimating capacity by 11% for birch and 39% for LDW connections. These results underscore the inadequacy of the conventional Johansen model when predicting wooden dowels, as it does not capture the observed failure behavior of wooden dowels.

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