



Laboratory Tests and Theoretical Analysis of Shear Joints Made of European Birch Plywood Embedded in the CLT Panels with European Beech Wooden Dowels

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This article presents a part of a broader study of the unique authors' solution for the joints of the walls made of CLT panels. The presented research concerns double shear butt joints with false tongue using the wooden, European beech dowels. They are joining the CLT panels and the load transferring European birch plywood embedded in the CLT panel axial plane, parallel to the lamellae. Also, an attempt was made to estimate the strength of such connections using empirical models included in the new EN 1995-1-1:2025 (EC5) standard. It was proved that in case when the assumptions of the EC5 are not met, i.e., the embedment depth is less than twice the diameter of the dowel, these models may lead to a significant overestimation of the load-bearing capacity of the wooden dowel connection. In particular, if the standard assumptions, such as the ratio of the wooden dowel diameter to the dowel embedment thickness, are not met. Comparison of the results of the laboratory tests with the load-bearing capacity determined theoretically according to the models included in EC5 showed its overestimation in the range of 23–51% in relation to the average tests' values, and 51–86% in relation to the nominal tests' values. Taking into account that the failure modes of wooden fasteners, due to the wood structure, may differ significantly from the metal ones, it is recommended to consider additionally also the Mode V of failure in the double plane shear joints with wooden dowels proposed by Miller et al. (2010).

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Introduction

The use of wooden dowels in timber structure connections has been practiced for a very long time. They are common in existing timber structures of historic buildings and in roof trusses of buildings constructed in the first half of the 20th century or earlier. These dowels were

made of both softwood and hardwood. The world's tallest timber structure, which is the 111-meter-high Gliwice Radio Tower (Fig. 1), was built in 1935 with the use of the wooden screws made of oak, which were later replaced with brass ones. Fig. 2 shows a detail of the original screw removed from a connection at the top of the tower. However, the development of steel fasteners such as nails,

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Fig. 1. View of the Gliwice Radio Station tower (built in 1935)



Fig. 2. Detail of the original wooden screw originally built in the structure of the Gliwice Radio Station tower (Fig.1)

screws, and, more recently, wooden screws has led to the diminishing of the wooden dowels from connections and their replacement with metal fasteners or metal joints.

Currently, the wooden dowel fasteners can become a valuable alternative to metal ones in many practical applications, due to their compatibility with timber elements and ease of disassembly and reuse. The advantage of connections made using wooden dowels is the ability to easily recycle entire sections of the structure. Additionally, wooden dowels are characterized by good fire resistance and are often used to protect steel dowels in the joint from high temperatures during a fire (Abrahamsen et al., 2014).

The literature contains numerous studies on the use of wooden dowels made of both hardwood and softwood in shear joints. Wang et al. (2025) and Tomasi et al. (2025) presented studies on multiple shear planes' joints of glued laminated timber to birch plywood with 20 mm diameter wooden dowels made of birch, beech, and densified red beech. Xu et al. (2022) investigated 12 mm diameter dowels made of densified poplar in three-element

shear joints made of glued laminated timber. Mehra et al. (2014) used 10 mm diameter wooden dowels made from densified Scots pine in their study of bending beams made from Douglas fir, connected in mid-span with densified wood inserts. Arciszewska-Kędzior et al. (2016) studied Norway spruce beams connected by lap joints (single or double) using 6 mm diameter wooden dowels made of European beech. El-Houjeiri et al. (2019) studied multilayer beams connected with wooden dowels and analyzed three-element shear connections with 16 mm diameter oak dowels. Brieden et al. (2023) tested diagonally embedded beech dowels ($\varnothing 10$ mm) for pull-out in LVL/LVL and OSB/LVL connections, taking into account different dowel inclination angles, and studied three-element connections made with diagonally embedded beech dowels in a C24 spruce timber connection inside with an OSB board placed outside. Aloisio et al. (2025) studied GL30c spruce glulam joints with birch plywood on both sides and used 20 mm diameter birch and densified red beech dowels in their tests. Zhang et al. (2025) investigated prestressed shear connections on three-element models made of pine *sylvestris* and spruce, and using 30 mm diameter beech dowels.

Small-diameter wooden dowels made of densified beech wood, known as wooden nails, are increasingly being used in shear connections. Ruan et al. (2022) studied single shear connections made of the strength grade C24 boards connected with 4.7 mm and 5.3 mm diameter wooden nails (Lignoloc®) made of compressed European beech.

In the research of Fan et al. (2025), clearly different failure mechanisms were observed: connections made with wooden nails exhibited a characteristic brittle failure mode, while steel fasteners exhibited a yield failure mode due to nail withdrawal and bending.

In addition to their use as fasteners in structural joints, wooden dowels are also used to connect lamellae to create non-glue-laminated timber beams or sandwich panels similar to glued laminated timber or CLT, respectively. Examples of non-glue-laminated, multi-layer beams joined with dowels can be found in Yeh et al. (2024), who investigated beams made of *Cryptomeria japonica*, from Taiwan, joined from eight boards using 19 mm diameter *Shorea* spp. dowels set at a 45-degree inclination angle. Similar studies were also conducted by O'Loinsigh et al. (2012 a and b). Zhang et al. (2025) used 30 mm diameter beech dowels to join logs in the log walls. In these joints, the wooden dowels primarily transfer shear forces across the joint, but the dowel itself is subjected to the complex stress state because it is subjected to simultaneous bending, shearing, and bearing across the grain.

Over the years, numerous studies have been conducted on the use of wooden dowels in building structures. These studies have shown, among other things, that connections using metal dowels can differ

significantly from those using wooden dowels. These differences result from the significant difference in the specific gravities between steel and wooden fasteners, as well as the differences in the material properties of wooden vs. steel dowels (anisotropy vs. isotropy). The comparable specific gravities of wooden dowels and the base material (timber) are also significant, as opposed to the much denser steel fasteners.

The currently applicable harmonized Eurocode 5 does not explicitly address the use of timber dowels in connections. This standard incorporates the European Yield Model (EYM), based on the Johansen (1949) calculation model developed for connections with metal dowels. However, the mechanical behavior of wooden fasteners

differs significantly from that of metal fasteners. Proper evaluation of connections with the wooden fasteners requires determining mechanical properties such as maximum bending strength, shear strength, and embedment strength. However, the elastic behavior of wooden fasteners and the variety of wood-based materials, their size, and geometry make determining these properties difficult.

The theoretical model applied in the EN 1995-1-1:2025 is mainly focused on the calculation of shear connections with metal fasteners. This model is based on the bending resistance of the fastener and the crushing strength of wood according to Johansen's theory, presented in equations 1a-1f. It takes into account possible modes of failure (Fig. 3) using metal dowels in single shear:

$$F_{D,k} = \min \left\{ \begin{array}{l} f_{h,1,k} \cdot t_{h1} \cdot d \quad (1a) \\ f_{h,2,k} \cdot t_{h2} \cdot d \quad (1b) \\ \frac{f_{h,1,k} t_{h1} d}{2 + \beta} \left[\sqrt{\beta + 2\beta^2 \left[1 + \frac{t_{h2}}{t_{h1}} + \left(\frac{t_{h2}}{t_{h1}} \right)^2 \right] + \beta^2 \left(\frac{t_{h2}}{t_{h1}} \right)^2} - \beta \left(1 + \frac{t_{h2}}{t_{h1}} \right) \right] \quad (1c) \\ 1.05 \frac{f_{h,1,k} t_{h1} d}{2 + \beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(2 + \beta)M_{y,k}}{f_{h,1,k} d t_{h1}^2}} - \beta \right] \quad (1d) \\ 1.05 \frac{f_{h,1,k} t_{h2} d}{1 + 2\beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(1 + 2\beta)M_{y,k}}{f_{h,1,k} d t_{h2}^2}} - \beta \right] \quad (1e) \\ 1.15 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2M_{y,k} f_{h,1,k} d} \quad (1f) \end{array} \right.$$

where:

$$\beta = \frac{f_{h2,k}}{f_{h1,k}} \quad (2)$$

$f_{h1,k}$, $f_{h2,k}$ are the characteristic embedment strengths of members 1 and 2,

$M_{y,k}$ is the characteristic yield moment of the metal fastener,

t_{h1} , t_{h2} are the embedment depths of members 1 and 2, e.g. wood or wood-based board,

d is the diameter of the fastener,

$F_{D,k}$ is the characteristic value of the dowel-effect contribution per shear plane.

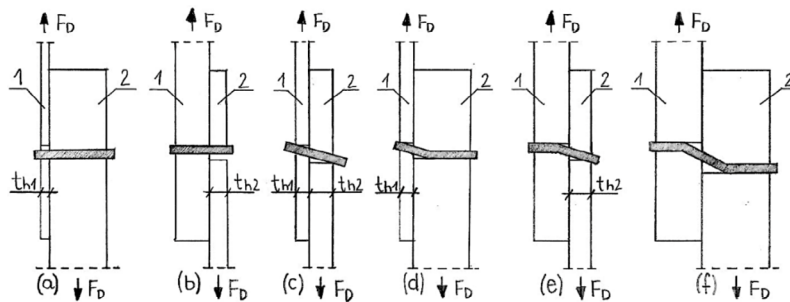


Fig. 3. Possible failure modes a) - f) for a fastener loaded in single shear

In addition, the EN 1995-1-1:2025 proposes a calculation model for shear connections with wooden dowels using the Johansen model (equations 1a–1f), however, with the following modifications and limitations:

- the factor 1.15 is replaced by 1.0,
- $M_{y,k}$ is replaced by $M_{u,k}$ (defined by equation 3),
- provided the following:
 - the round dowel with $12 \text{ mm} \leq d \leq 30 \text{ mm}$ diameter,
 - the wooden dowel is made from hardwood (Beech $f_{m,k} = 110 \text{ N/mm}^2$, Oak $f_{m,k} = 60 \text{ N/mm}^2$, Bongossi $f_{m,k} = 100 \text{ N/mm}^2$),
 - the wooden dowel is loaded in one- or two-shear planes,
 - the characteristic value of the density of the members in the joint is $\rho_k \geq 350 \text{ kg/m}^3$,
 - the minimum thicknesses of the timber members is $t_{h1} \geq 2d$ and $t_{h2} \geq 2d$,
 - all the spacing and distances for wooden dowels are greater than or equal to $2d$ except for the distances to the loaded end $a_{3,i}$, which is at least $\max(2d; 40 \text{ mm})$,
 - the clearance in the shear planes between the timber members is less than or equal to 1.5 mm.

$M_{u,k}$ is the characteristic ultimate bending moment of wooden dowels and is expressed by equation 3:

$$M_{u,k} = 0.75 \frac{\pi}{32} f_{m,k} d^3 \text{ [Nmm]} \quad (3)$$

In the case of calculations of connections with wooden dowels, equations 1 are modified by replacing the factor 1.15 in equation 1f with the factor 1.0, and by replacing $M_{y,k}$, the characteristic yield moment of the metal fastener in equations 1c–1f with $M_{u,k}$, the characteristic ultimate bending moment of a wooden dowel.

According to Tomasi et al. (2025), the factor 1.05 in the equations 1d and 1f should also be adjusted to 1.0, although this is not explicitly required by EN1995-1-1:2025, because the factors 1.15 and 1.05 were originally introduced to take into account the different partial safety coefficients k_{mod} for steel and wood, which is not applicable in the case of using wooden dowels. After modifications, equations 1a–1f in accordance with the provisions of the EN1995-1-1:2025 take the form of equations 4a–4f:

$$F_{D,k} = \min \left\{ \begin{array}{l} f_{h,1,k} \cdot t_{h1} \cdot d \quad (4a) \\ f_{h,2,k} \cdot t_{h2} \cdot d \quad (4b) \\ \frac{f_{h,1,k} t_{h1} d}{2 + \beta} \left[\sqrt{\beta + 2\beta^2 \left[1 + \frac{t_{h2}}{t_{h1}} + \left(\frac{t_{h2}}{t_{h1}} \right)^2 \right] + \beta^2 \left(\frac{t_{h2}}{t_{h1}} \right)^2} - \beta \left(1 + \frac{t_{h2}}{t_{h1}} \right) \right] \quad (4c) \\ 1.05 \frac{f_{h,1,k} t_{h1} d}{2 + \beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(2 + \beta)M_{u,k}}{f_{h,1,k} d t_{h1}^2}} - \beta \right] \quad (4d) \\ 1.05 \frac{f_{h,1,k} t_{h2} d}{1 + 2\beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(1 + 2\beta)M_{u,k}}{f_{h,1,k} d t_{h2}^2}} - \beta \right] \quad (4e) \\ 1.0 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2M_{u,k} f_{h,1,k} d} \quad (4f) \end{array} \right.$$

where $f_{h1,k}, f_{h2,k}$ are the characteristic embedment strengths of members 1 and 2, determined from the equation 5:

$$f_{h,k} = 10^{-4} \rho_{dowel,k} \rho_k \frac{1.1(1 - 0.01d)}{(3.4 - 0.045d) \sin^2 \alpha + \cos^2 \alpha} \quad (5)$$

where $\rho_{dowel,k}$ is the characteristic density of the wooden dowel.

In the case of connections in double shear, the failure modes 4c and 4e do not occur (Fig. 4), and therefore equations 4a–4f should be written as in the following equations 6a–6f:

$$F_{D,k} = \min \left\{ \begin{array}{l} f_{h,1,k} \cdot t_{h1} \cdot d \quad (6a) \\ f_{h,2,k} \cdot t_{h2} \cdot d \quad (6b) \\ 1.05 \frac{f_{h,1,k} t_{h1} d}{2 + \beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(2 + \beta)M_{u,k}}{f_{h,1,k} d t_{h1}^2}} - \beta \right] \quad (6d) \\ 1.0 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2M_{u,k} f_{h,1,k} d} \quad (6f) \end{array} \right.$$

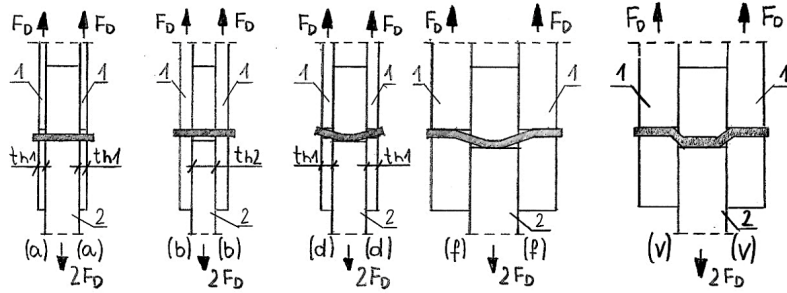


Fig. 4. Possible failure modes a), b), d), f) and Mode V of failure for a fastener loaded in double shear

Various studies have shown that the grain direction, dowel diameter, and thickness of the central and lateral elements of the joint strongly influence the failure mechanism and shear resistance of doweled wooden connections. Unlike steel dowels, the wooden dowels have mechanical properties (e.g., strength and stiffness) similar to those of the wooden elements in the joint, leading to failure modes beyond those considered by Johansen's theory. Sandoli et al. (2023) demonstrated that the European Yield Model (EYM) from Eurocode 5 generates inaccurate results for timber connections using timber pegged joints and requires modification. Also, Tomasi et al. (2025) demonstrated, based on tests of 20 mm diameter wooden dowels in combination with birch plywood, that the applied model according to EN 1995-1-1:2025 significantly overestimated the resistance obtained in the test for wooden dowels or, more generally, timber pegs.

Also, in the Fan et al. (2025) study conducted on compressed beech nails (50 mm long and 4.7 mm in diameter) embedded in the Scots pine wood, clearly different failure mechanisms were observed: the wooden nail joints showed a characteristic brittle failure mode, while the steel joints were characterized by yield failure involving ductile nail withdrawal accompanied by bending deformation.

Tomasi et al. (2025) and Vilguts et al. (2024) present studies on the use of larger diameter wooden dowels in double shear connections and refer to the Miller et al. (2010) model, which takes into account the combined effects of bending, shear and bearing perpendicular to the grain of the wooden dowel in the connection, called the 'effective peg shear yield mode' or Mode V

of failure. Tomasi et al. (2025) and Vilguts et al. (2024) in their works refer to the calculation model by Miller et al. (2010) expressed with equation 7:

$$F_{D,k} = \frac{\pi d^2 f_v}{4} \quad (7)$$

where:

$F_{D,k}$ is the Mode V of failure force for hardwood dowels, f_v is the shear yielding stress according to equation 8:

$$f_v = 33.4 G_{dowel} G_{base}^{0.75} \quad (8)$$

where:

$$G_{dowel} = \frac{\rho_{dowel}}{\rho_w} \quad (9)$$

$$G_{dowel} = \frac{\rho_{base}}{\rho_w} \quad (10)$$

where: ρ_{dowel} , ρ_{base} and ρ_w are the specific gravities of the hardwood dowel, the base material (the embedding material, timber) in the joint, and the water (the embedding medium).

As can be seen from the above equations, in the Miller et al. (2010) model, the specific gravity of wooden dowels plays a key role in the mechanical parameters for Mode V of failure for hardwood dowels.

Materials and methods

Shear load-bearing capacity tests were performed for a single wooden dowel with a diameter of 22.0 mm, in double plane shear, in a connection of a CLT panel with a plywood (21 mm thick) inserted into sockets made in the axial plane of a CLT panel with a thickness of 100 mm.

The wooden dowel was made of European beech (*Fagus sylvatica* L.) with an average density of 705.3 kg/m³, and a moisture content during the test of approx. 7% ±1%. The 21 mm thick internal plywood was made of 15 layers

of European birch (*Betula pendula* Roth L.) veneer, with a density of 680 kg/m³, longitudinal compressive strength of 23.6 MPa, and moisture content of approx. 12% ±1%. The CLT boards were five-layered (made of 20 mm lamellas) made of Norway spruce (*Picea abies* (L.) H. Karst) with a density of 350 kg/m³, and moisture content of approx. 10% ±2%.

Three series of the test samples were prepared for the tests, reflecting the possible nature of work in the joints of vertical CLT wall panels:

- R-type sample (Fig. 5) reflecting the possibility of tensile forces acting in the connection between CLT panels,
- SW-type sample (Fig. 6) reflecting the possibility of shear forces acting in the joint between CLT panels, in which the lamellae grains adjacent to the plywood board ran parallel to the load direction (bearing along the grains),
- SP-type sample (Fig. 7) reflecting the possibility of shear forces acting in the joint between CLT panels, in which the lamellae grains adjacent to the plywood board ran perpendicular to the load direction (bearing across the grains).

The R-type joint specimens were made from the CLT panels, 100 mm thick, 200 mm wide, and 400 mm long. At both ends of the specimens, 21 mm thick and 105 mm deep sockets were placed in the center plane of the panel thickness to accommodate 21 mm × 180 mm, 415 mm long plywood boards inside the CLT panel. The specimen was connected to the plywood board using a 22.0 mm diameter wooden dowel. The shear capacity of the European beech (*Fagus sylvatica* L.) wood dowels in the R-type specimens was determined in tension, which corresponds to one of the real load cases, i.e., to test the joint behavior under the tensile forces in a wall made of CLT panels.

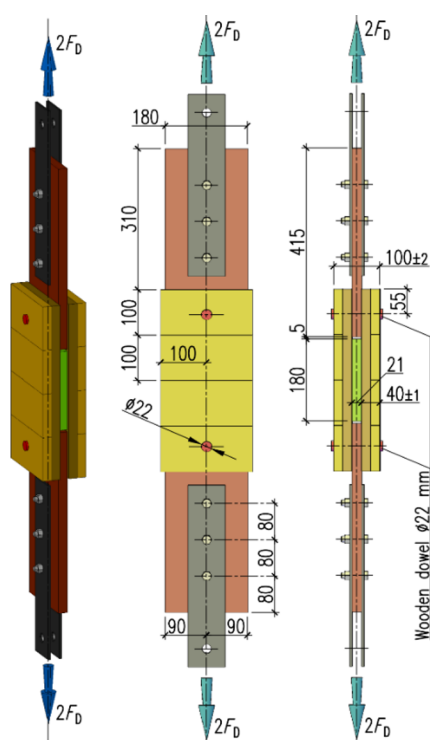


Fig. 5. Dimensions of the R-type specimen for tensile shear

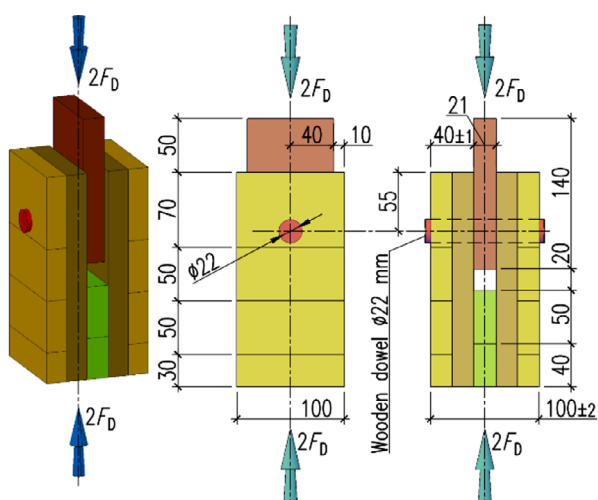


Fig. 6. Dimensions of the SW-type specimen for bearing 'along the grains'

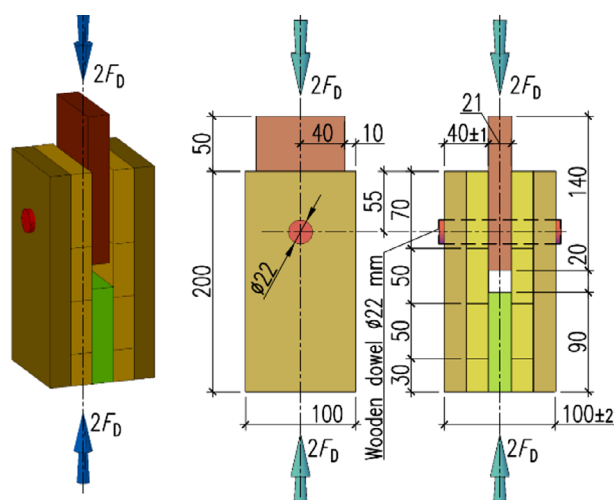


Fig. 7. Dimensions of the SP-type specimen for bearing 'across the grains'

The SW- and SP-type specimens were made of the 100 mm wide, and 200 mm high CLT panels. At one end of the specimens, 21 mm thick and 90 mm deep sockets were made in the center plane of the panel thickness to accommodate 21 mm thick, 80 mm wide, and 104 mm long plywood boards inside the CLT panel sample. The CLT panel was connected to the plywood board insert using a 22.0 mm diameter European beech dowel, which was assembled in holes with a diameter of 22.0 mm made in plywood and CLT panel in the model axis. The shear capacity of the wood dowels in the SW- and SP-type samples was determined in compression, which also corresponds to the possible load acting on the connections in the case of horizontal forces transferred by the stiffening walls made of the CLT panels.

The test was conducted on a LabTest 6.50 testing machine with a load range of up to 50 kN in the Civil

Engineering Laboratory of the Silesian University of Technology, at a temperature equal to $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and a relative humidity of $60\% \pm 5\%$.

The load was applied in the testing machine vertically, by displacement control. In accordance with the recommendations given in PN-EN 12512:2002/A1:2006, a constant displacement increment of approximately 0.03 mm/s was assumed for the test. The test time for each specimen was approximately 300 ± 120 seconds.

The displacements in the dowel joint were measured using four LVDT sensors of PSx25-type for the R-type sample and two LVDT sensors of PSx25-type for the SW- and SP-type ones, attached symmetrically on both sides of the specimens to the external lamellae plane and the center birch plywood board. The tests were conducted under static, instantaneous load. The specimens were unloaded when

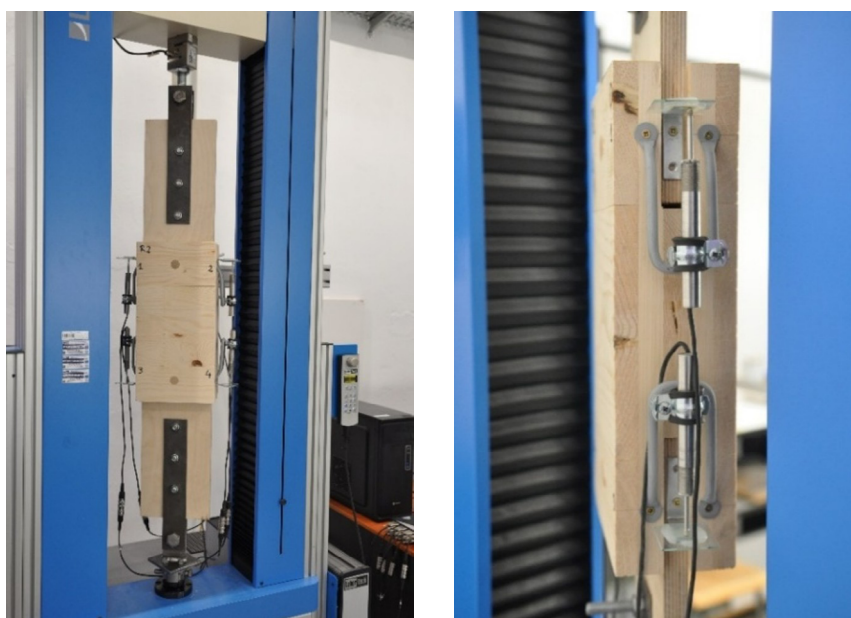


Fig. 8. View of the test stand for the R-type specimens: a) general view, b) LVDT sensor

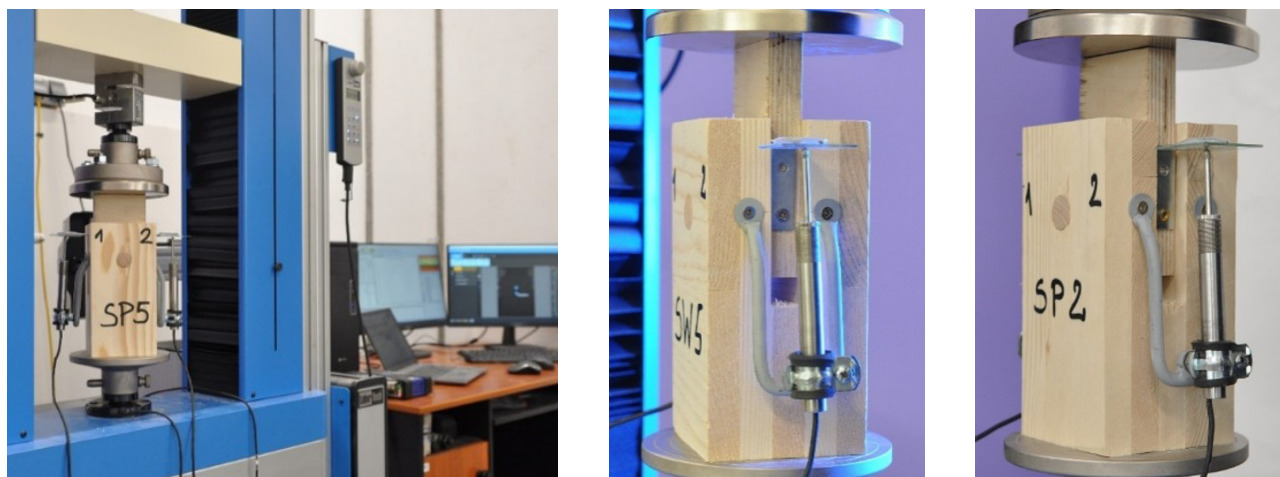


Fig. 9. View of the test stand: a) general view, b) SW-type specimen, c) SP-type specimen

a significant increase in displacements was measured in the dowel joint.

In the shear test of a beech dowel in a double shear joint under tension, 1020 mm long R-type specimens were mounted in a testing machine. They were connected to a test frame and a vertically movable upper head using hinged connections. Steel plates measuring $60 \times 4 \times 340$ mm were used at both ends of the joint specimens to secure them in the testing machine jaws. The specimens were connected to the steel anchors using three $M12 \times 60$ strength grade 5.6 bolts, embedded in holes with a diameter of 12 mm (in plywood and steel plates), spaced at 80 mm, with the bolt's distance from the edge of the wooden element equal to 80 mm. A view of the test stand is shown in Fig. 8.

The views of the test stand for the SW- and SP-type samples are shown in Fig. 9. The arrangement of the lamellae in relation to the load direction is shown in Fig. 9b for the SW- and in Fig. 9c for the SP-type specimens.

Results and discussion

Due to the lack of current standard provisions regarding the principles of testing connections with wooden dowels, the same test methods as for the metal fasteners were used, in accordance with the

PN-EN 12512:2002/A1:2006 and PN-EN 26891:1997. Fig. 10 presents the 'force-displacement' ($2F_D-v$) plots for the R-type sample. The v -displacement values are averaged from 4 LVDT sensors. Fig. 12 and Fig. 13 present the 'force-displacement' ($2F_D-v$) plots for the SW- and SP-type samples, respectively. In this case, the v -displacement values are averaged from 2 LVDT sensors.

Based on the test results, the joint yield strength $2F_D$ was determined according to Eurocode PN-EN 1995-1-1:2010/NA:2010 at the intersection of the two following lines describing the variation of the 'force-displacement' ($2F_D-v$) relationship for two ranges: before and after the joint yielding, as shown in Fig. 11.

The summary of the results of strength tests in double shear is given in Table 1, while the joint yield strength values are given in Table 2. The failure modes occurring in the 'SW' sample are shown in Fig. 14a, while Fig. 14b shows failure modes for the 'SP' sample. In the 'R' sample, the failure modes analogous to those observed in the 'SW' series were observed. These figures illustrate a different failure mode from the steel dowels, which are made of homogeneous, isotropic, and highly ductile material. In our tests, we are dealing with an anisotropic material whose

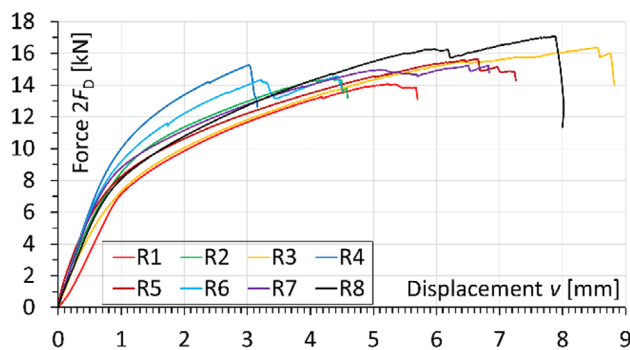


Fig. 10. Force-displacement ($2F_D-v$) plot for the R-type sample

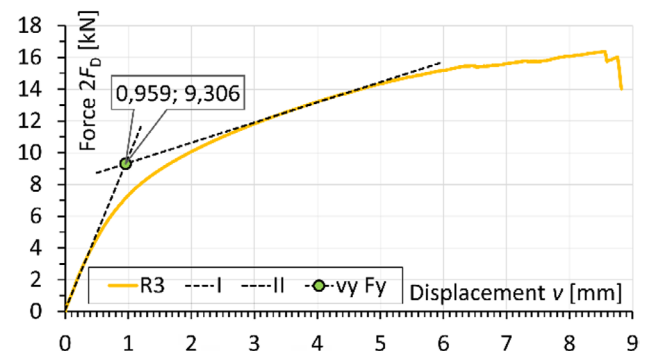


Fig. 11. Determination of the joint yield strength for the 'R3' specimen

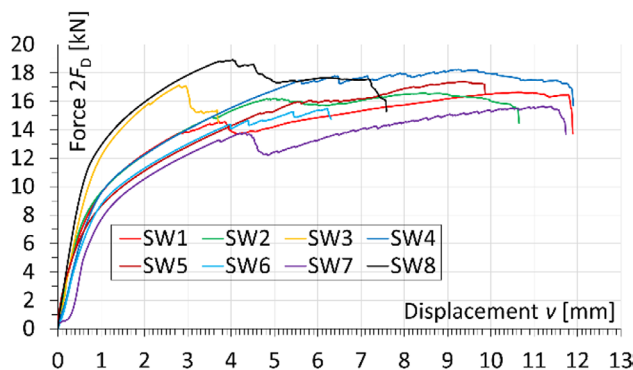


Fig. 12. Force-displacement ($2F_D-v$) plot for the SW-type sample

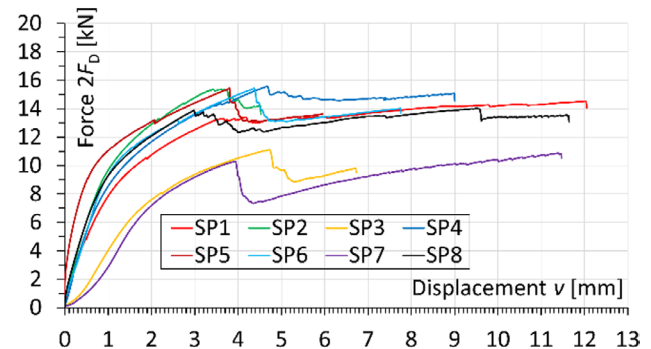


Fig. 13. Force-displacement ($2F_D-v$) plot for the SP-type sample

Table 1. Test results of joint samples

No.	Sample	Specimen	Maximal force	Joint yield strength	Joint yield slip	Joint slip modulus
			$2F_{D,max}$ [kN]	$2F_D$ [kN]	v_y [mm]	K_s [N/mm]
1	R	R1	14.07	8.672	1.133	8211
2		R2	14.39	9.868	0.975	9590
3		R3	16.37	9.306	0.959	9593
4		R4	15.27	10.456	0.841	12278
5		R5	15.64	9.676	0.921	9323
6		R6	14.26	10.193	0.852	11693
7		R7	15.24	9.562	0.826	11346
8		R8	17.06	10.056	1.013	9765
1	SW	SW1	16.63	9.887	0.669	14387
2		SW2	16.58	10.160	0.664	14801
3		SW3	17.11	12.392	0.786	15692
4		SW4	18.23	11.097	0.977	11279
5		SW5	17.38	9.464	0.788	10040
6		SW6	15.49	9.740	0.895	11025
7		SW7	15.65	8.665	0.862	14247
8		SW8	18.91	13.933	0.742	18476
1	SP	SP1	14.52	8.864	0.925	9143
2		SP2	15.35	10.840	0.975	10222
3		SP3	11.12	8.177	1.881	4767
4		SP4	15.57	10.426	0.996	10313
5		SP5	14.46	10.769	0.833	12714
6		SP6	15.43	10.926	1.070	9889
7		SP7	10.87	7.802	1.974	5038
8		SP8	14.02	10.183	0.962	9186

Table 2. Determination of the joint yield strength $2F_D$

No.	Sample	Number of specimens [pcs]	Joint yield strength $2F_D$ [kN]			Standard deviation $2F_D$ [kN]
			Mean $2F_{D,avg}$	Maximum $2F_{D,max}$	Minimum $2F_{D,min}$	
1	R	8	9.724	10.456	8.672	0.56
2	SW	8	10.667	13.933	8.665	1.73
3	SP	8	9.748	10.926	7.802	1.27

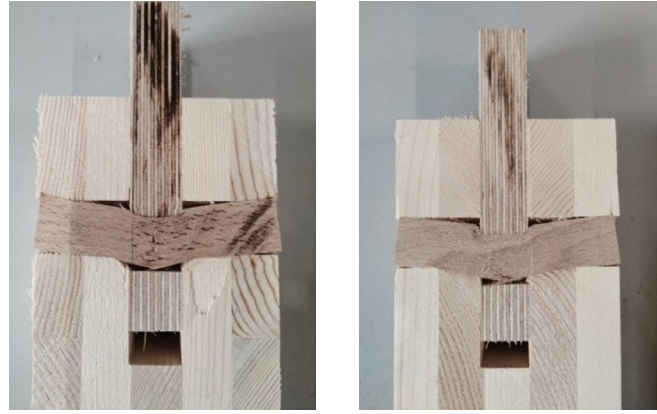


Fig. 14. The failure modes: a) SW-type specimen, b) SP-type specimen

transverse strength and strain are significantly lower than the strength and strain along the grain. Figures 11a and 11b show a failure mode largely determined by the strain and transverse strength of both the dowel and wood in the CLT panel.

Discussion of the test results

The test results were verified according to EN 1995-1-1:2025 and the Miller et al. (2010) theoretical failure mode called ‘effective peg shear yield mode’ or Mode V of failure, considered by Tomasi et al. (2025) and Vilguts et al. (2024).

When determining the load-bearing capacity of the tested connection between CLT panels and European birch plywood using European beech dowels, according to the models included in EN 1995-1-1:2025, it should be noted that the connections in each from the test R-, SP- and SW-samples did not meet the dowel embedment depth requirements defined as: $t_{h1} \geq 2d$ and $t_{h2} \geq 2d$, where $t_{h1} = 19.5$ (39.5) mm and $t_{h2} = 21$ mm which are the embedment thickness in the CLT (t_{h1}) and the embedment thickness in the European birch plywood board (t_{h2}), respectively, and $d = 22.0$ mm is the diameter of the European beech dowel.

The following assumptions were made to calculate the load-bearing capacity in single shear of the beech dowel in the analyzed tests:

- in the specimens in which the wood grains of the lamellae adjacent to the load transferring plywood board ran parallel to the load direction – only the thickness of the adjacent layer was assumed as the

embedding thickness, i.e., $t_{h1} = 19.5$ mm, and the characteristic embedment strength was provided, in the specimens in which the wood grains of the lamellae adjacent to the load transferring plywood board ran perpendicular to the load direction – the total thickness of the wood layer in single shear was assumed as the embedding thickness, i.e., $t_{h1} = 39.5$ mm and the characteristic embedment strength was provided.

According to equation 3, the characteristic ultimate bending moment for a beech wooden dowel is equal to:

$$M_{u,k} = 0.75 \frac{\pi}{32} 110 * 22^3 = 86\,242.6 \text{ Nmm} \quad (11)$$

where:

d is diameter of beech dowel = 22 mm,

$f_{m,k}$ is the characteristic bending strength of beech wood equal to 110 N/mm² – according to section 11.2.3.4(1) of EN 1995-1-1:2025.

The characteristic embedment strength of a beech dowel to a CLT wood layer with the grain arrangement parallel to the load direction was calculated according to equation 5, assuming the specific gravity of the beech dowels used in the tests, which is 705.3 kg/m³, and the density of CLT wood as 350 kg/m³, which comply with the CLT panels made of C24 spruce, used in the tests. For such assumed densities, $f_{h1,0,k}$ – the characteristic embedment strength of a beech dowel to a CLT wood layer with the grain arrangement parallel to the load direction is equal to:

$$f_{h1,0,k} = 10^{-4} * 705.3 * 350 \frac{1.1(1 - 0.01 * 22)}{(3.4 - 0.045 * 22) \sin^2 0 + \cos^2 0} = 21.2 \text{ N/mm}^2 \quad (12)$$

Whereas $f_{h1,90,k}$ – the characteristic embedment strength of a beech dowel to a CLT wood layer with the grain arranged perpendicularly to the load direction is equal to:

$$f_{h1,90,k} = 10^{-4} * 705.3 * 350 \frac{1.1(1 - 0.01 * 22)}{(3.4 - 0.045 * 22) \sin^2 90 + \cos^2 90} = 8.7 \text{ N/mm}^2 \quad (13)$$

and $f_{h2,k}$ – the characteristic embedment strength of a beech dowel on birch plywood with a density of 680 kg/m³ is equal to:

$$f_{h2,k} = 10^{-4} * 705.3 * 680 \frac{1.1(1 - 0.01 * 22)}{(3.4 - 0.045 * 22) \sin^2 0 + \cos^2 0} = 41.1 \text{ N/mm}^2 \quad (14)$$

For those load-bearing capacities of the beech dowel in single shear, the load-bearing capacity of the joint in single shear was determined according to equations 6a–6f, taking into account the results from equations 11–14 and the above-mentioned assumptions of thicknesses t_{h1} and t_{h2} .

Therefore, the characteristic load-bearing capacity of the joint in single shear is equal to 6.560 kN and 7.381 kN for the SW- and SP-type specimens, obtained as the minimum value from equations 15 and 17, respectively:

$$F_{D,k(SW)} = \min \left\{ \begin{array}{l} 21.2 \cdot 19.5 \cdot 22 = 9094.8 \text{ N} \\ 40.8 \cdot (0.5 \cdot 21) \cdot 22 = 9494.1 \text{ N} \\ 1.05 \frac{21.2 \cdot 19.5 \cdot 22}{2 + 1.94} \left[\sqrt{2 \cdot 1.94 \cdot (1 + 1.94) + \frac{4 \cdot 1.94 \cdot (2 + 1.94) \cdot 86243}{21.0 \cdot 22 \cdot 19.5^2}} - 1.94 \right] = 6559.7 \text{ N} \\ 1.0 \sqrt{\frac{2 \cdot 1.94}{1 + 1.94}} \sqrt{2 \cdot 86243 \cdot 21.0 \cdot 22} = 10255.1 \text{ N} \end{array} \right. \quad (15)$$

where:

$$\beta = \frac{f_{h2,k}}{f_{h1,0,k}} = \frac{41.1}{21.2} = 1.94 \quad (16)$$

Whereas:

$$F_{D,k(SP)} = \min \left\{ \begin{array}{l} 8.7 \cdot 39.5 \cdot 22 = 7560.0 \text{ N} \\ 40.8 \cdot (0.5 \cdot 21) \cdot 22 = 9494.1 \text{ N} \\ 1.05 \frac{7560.0}{2 + 4.72} \left[\sqrt{2 \cdot 4.72 \cdot (1 + 4.72) + \frac{4 \cdot 4.72 \cdot (2 + 4.72) \cdot 86243}{8.7 \cdot 22 \cdot 39.5^2}} - 4.72 \right] = 10948.9 \text{ N} \\ 1.0 \sqrt{\frac{2 \cdot 4.72}{1 + 4.72}} \sqrt{2 \cdot 86243 \cdot 8.7 \cdot 22} = 7381.3 \text{ N} \end{array} \right. \quad (17)$$

where:

$$\beta = \frac{f_{h2,k}}{f_{h1,90,k}} = \frac{41.1}{8.7} = 4.72 \quad (18)$$

Comparing the test results with calculations according to the EN 1995-1-1:2025, it should be noted that the theoretical results significantly overestimate the test results. With respect to the mean joint yield strength $2F_{D,mean}$, according to Table 1, the theoretical values were overestimated by 23% and 51% for the SW- and SP-type samples, respectively, and by 34% for the R-type sample. However, with respect to the minimum joint yield strength $2F_{D,min}$, the values were overestimated by 51%, 89%, and 51% for the SW-, SP-, and R-type samples, respectively. However, it should be emphasized that the thicknesses of the joint elements (particularly the birch plywood board) did not meet the standard requirements, and they were very similar to the diameter of a beech dowel.

By performing a comparative analysis according to the equations given in the works of Tomasi et al. (2025) and Vilguts et al. (2024), i.e., equations 7–10, the theoretical yielding force for the V-mode of failure for hardwood dowels is equal to:

$$F_{D,k} = \frac{\pi \cdot 22^2 \cdot 10.73}{4} = 4095.2 \text{ [N]} \quad (19)$$

in which the shear yielding stress, taking into account equations 8–10, is equal to:

$$f_v = 33.44 \cdot 0.705 \cdot 0.350^{0.75} = 10.73 \text{ [N/mm}^2\text{]} \quad (20)$$

Comparing the results obtained from the tests with the theoretical calculations according to the failure mode considered in the works by Tomasi et al. (2025) and Vilguts et al. (2024), it was found that the theoretical shear yielding stress f_v (equation 20) does not depend on the direction of the lamellae grains adjacent to the plywood board nor on the embedment thicknesses in the plywood board and in the CLT plate. Instead, the theoretical shear yielding stress f_v is directly dependent on the density of the materials in the joint. This finding estimates the load-bearing capacity of the joint significantly better.

The theoretical yielding force means 75% and 84% of $2F_{D,mean}$ - the mean joint yield strength obtained in the tests for the R- and SW-type samples, respectively, in which the wood grains of the lamellae adjacent to the load transferring plywood board ran parallel with the load direction, and 84% of $2F_{D,min}$ - the minimum joint yield strength for the SP-type sample in which the wood grains of the lamellae adjacent to the load transferring plywood board ran perpendicular to the load direction.

However, comparing the theoretical yielding force $2F_{D,k}$ with $2F_{D,min}$ - the minimum joint yield

strength, gives 94% of the test load-bearing capacity for the R- and SW-type samples and 105% for the SP-type sample.

Conclusions

This paper presents the results of the load-bearing capacity of a single, 22.0 mm diameter wooden (European beech) dowel in a double shear connection between CLT and the load-transferring European birch (*Betula pendula* Roth L.) plywood board placed inside the CLT board plane in a pre-milled groove. The test results were discussed with the use of the theoretical analysis based on the empirical models included in the new version of Eurocode 5 and the so-called Mode V of failure (also called as ‘effective peg shear yield mode’) proposed by Miller et al. (2010) and presented in Tomasi et al. (2025) and Vilguts et al. (2024) works.

The presented results provide a better understanding of connections using large-diameter wooden dowels under shear loads. These are interesting solutions, but the proposed empirical models should be approached with caution in case the current requirements of the EN 1995-1-1:2025 standard are not met, and therefore, further research works are necessary to better understand their performance depending on the wood species used, dowel diameter, and other joint components.

Based on research and theoretical analysis, the following main conclusions can be drawn:

1. Wooden dowels can effectively compete with steel dowels in creating connections in wooden structures. However, it should be emphasized that their modes of failure may differ significantly from the forms of failure of metal fasteners, especially when the dowel diameter is greater than 0.5 times its embedment depth.
2. When the current standard requirements for the pin embedment depth are not met, using larger diameter European beech (*Fagus sylvatica* L.) dowels, the failure modes proposed according to EN 1995-1-1:2025 may significantly overestimate the connection's load-bearing capacity. These observations are also confirmed by Tomasi et al. (2025) and Vilguts et al. (2024),
3. The load-bearing capacity was estimated much better by the Mode V of failure proposed by Miller et al. (2010) than the equations included in EN1995-1-1:2025. Due to the large variety of solutions and the range of wood materials, further work is necessary to identify possible failure modes and develop appropriate empirical models.

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Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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List of standards

- PN-EN 1995-1-1:2010/NA:2010** Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings
- EN 1995-1-1:2025** Eurocode 5: Design of timber structures – Part 1-1: General rules and rules for buildings
- PN-EN 12512:2002/A1:2006** Timber Structures – Test methods, Cyclic testing of joints made with mechanical fasteners
- PN-EN 26891:1997** Timber structures – Joints made with mechanical fasteners, General principles for the determination of strength and deformation characteristics.
- PN EN 13556: 2005** Round and sawn timber - Nomenclature of timbers used in Europe.
- PN-EN 16351:2021** Timber structures – Cross-laminated timber – Requirements.
- PN-EN 313-1:2001** Plywood – Classification and terminology. Part 1: Classification.