

Advancing Timber for the Future Built Environment

EXPERIMENTAL AND ANALYTICAL STUDY OF CONNECTIONS FOR LIGHT AND PURE TIMBER CONSTRUCTIONS WITH BENT WOOD

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ABSTRACT: This research focuses on developing connections for an innovative pavilion demonstrator using bent wood. The techniques of bending and compressing wood are employed here. The starting point for the demonstrator design was a spherical polyhedron with 132 pentagonal faces (132-Pentagon Polyhedron), which offers a highly symmetrical geometry from only three different shapes. The core of this work is to demonstrate the load-bearing capacity of the entire structure and especially the connections. For this purpose, models were created using the finite element method program. These models were used to determine the internal forces and stress distributions, which were then utilized for the design. Based on these results, the connections used in the structure were designed. Two types of mechanical connections are being tested: one purely wood-based (utilizing compressed wood) and the other incorporating steel bolts. The experimental phase involves bending, shear and push-out tests on the samples to evaluate their performance. This study aims to enhance the sustainability and structural efficiency of timber constructions by reducing reliance on adhesives. Key findings and methodologies are detailed in this paper, providing insights into the mechanical properties and feasibility of these connections.

KEYWORDS: Timber engineering, connections, bent wood, compressed wood, sustainability

1 – INTRODUCTION

Timber is considered a sustainable building material, but the use of adhesives in timber products poses environmental challenges. The research project presented in this paper aims to reduce the use of adhesives, promote cleaner production methods and facilitate easier recycling of timber components. This initiative builds on the innovative "BenDit" structure [1] & [2], which was developed within the European project Adhesive-Free Timber Buildings (AFTB). In this research two types of mechanical connections are evaluated: one purely woodbased, using compressed wood (CW) and one incorporating steel. A key outcome of this research project will be a demonstrator pavilion (See Figure 1) at TU Dresden, displaying the feasibility and sustainability of these innovative construction methods. The design of the connection concepts is based on the structural requirements defined in Eurocode 5 for mechanical fasteners, as well as findings from previous experimental and analytical studies [3] & [4]. The aim was to investigate the load-bearing capacity, rotational behaviour and ductility of the developed joints. Particular emphasis is placed on connections using compressed beech wood dowels and conventional steel bolts.

2 – BACKGROUND

Historically, the timber industry has been dependent on softwood due to its vast availability and easy processing,

which has limited the technological development in hardwood utilization. However, current industrial practices result in significant material loss in the production of softwood products; up to approximately 60% of the wood is wasted during processing [5]. According to Kollmann [6], bent wood manufacturing has several advantages over machining curved shapes including lower material loss and reduced costs. Bending is faster, simpler and increases the strength and stiffness of wood due to the high forces involved, similar to wood compression [7] & [8].



Figure 1: Design of the pavilion demonstrator

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Steam bending is a state-of-the-art technique in the furniture industry, rooted in centuries-old craftsmanship and still widely used today.

For the mechanical connections, compressed wood dowels were produced using the thermo-hydromechanical (THM) densification process, which enhances the material's strength [9] & [10]. This process involves compressing wood between heated plates at around 120°C, reducing its height by approximately 50%, which significantly increases its density and strength [11] & [12]. Building upon these findings, the present research applies bending and densification processes to structural connections in timber construction. European beech wood is used due to its favourable properties under bending and compression, ensuring robust and sustainable connections for the timber structure. Densified beech can achieve very high density and strength, making it an ideal material for allwood dowel connectors in this context.

3 – DEMONSTRATOR

3.1. DESIGN

A spherical polyhedron, more precisely a 132-pentagon polyhedron, was selected as the basis for the calculations. In the further course of the investigations, we intend to construct free-form surfaces. A spherical polyhedron, more precisely a 132-pentagon polyhedron, was selected as the basis for the calculations. In the further course of the investigations, we intend to construct free-form surfaces. However, in order to obtain better comparative values, we exploit the rotational symmetry of this polyhedron. To adapt the structure for a roof or dome, it was cut in half. The 132-pentagon polyhedron consists of 12 regular pentagons and 2 x 60 mirror-symmetric pentagons, which have a total of 5 different edge lengths. Thus, our version with additional openings as entry and exit has 66 pentagons, 6 of which are regular and two sets of 30 each contain mirror-symmetric ones. We added 10 quadrilateral elements and foundations to make the entrances high enough. The polyhedron was scaled so that the largest element corresponds to a circumference of 280 cm with a corner radius of 10 cm. The dihedral angles are 15.57°, 19.39°, 18.15°, 18.77° and 19.39°, respectively, from the smallest to the largest edge, with occurrences of 60, 30, 60, 120 and 60. The regular pentagons are surrounded by groups of 5 mirrorsymmetric pentagons each and the second set of pentagons occurs in rotationally symmetric groups of 3 (see Figure 2). It can be assumed that in finer discretized surfaces the dihedral angles can become even smaller. This complex geometry requires connections that can accommodate different intersection angles and fabrication tolerances while maintaining structural integrity. An adhesive-free, all-timber connection approach was prioritized for sustainability, inspired by the BenDit sculpture concept. Therefore, two mechanical connection concepts were developed and evaluated: a CW dowel connection and a steel bolt connection. Each connection joins two bent wood frame members and a custom-shaped spacer block at the node. The wedgeshaped spacer fills the gap between the inclined members, ensuring proper contact and force transfer geometry. Both connection types use a single fastener running through the two bent wood elements and the wedge, clamping the joint together.



Figure 2: Dimensions of the different bentwood frames

3.2. ANALYTICAL MODELLING AND STRUCTURAL ANALYSIS

To evaluate the global structural behaviour of the bent wood pavilion, a numerical model was created in RFEM (finite element method software by Dlubal). The structure was modelled as half-dome using beam elements. Each bent wood element was modelled as a beam (one-dimensional bar element) with the crosssection 25×100 mm (rectangular) and material properties of beech wood (assumed strength class D40, consistent with European beech). The curved shape of each element was modelled by segmenting it into straight beam segments following the polyhedral edges and then refining at the corners; a minimum bending radius was applied at the sharp corner transitions to reflect the curvature limitations of steam-bent beech. To simplify modelling, only a 1/5 segment of the symmetric dome was initially modelled manually; this segment was then mirrored and rotated to generate the complete dome structure, taking advantage of the pavilion's rotational symmetry. Connections were assumed as pin joints using beam elements. A circular cross-section of 20 mm diameter was used for the wood dowel (material properties corresponding to densified beech, approx. class D80 hard wood).

The dome structure was assumed to be supported at its base where it interfaces with foundation blocks. In the model, each foundation interface was modelled with support constraints. To avoid over-constraining the structure, the base supports were modelled as pinned or roller supports. Specifically, each base node had a vertical support (preventing settlement) and a lateral support; however, some lateral supports were released in one horizontal direction to allow the dome to expand or contract slightly under load, simulating a realistic foundation that does not fully clamp all degrees of freedom. The pavilion was analysed under self-weight, snow and wind loads according to Eurocode 1. Snow loads included uniform and asymmetric scenarios and wind loads were applied from two main directions (0° and 90°). Load combinations (16 in total) were evaluated for critical internal forces.

The self-weight of all bent wood members and connectors was included automatically via the material densities. Beech wood at ~700 kg/m³ for D40 and densified beech at ~1200 kg/m³ for D80 were used for weight calculation. The weight of the intermediate wooden wedges, which were not modelled as solid elements, was applied as an equivalent line load on the adjacent beams. Each wedge's weight was calculated from its volume and an assumed density of 660 kg/m³ (solid beech) and then distributed equally to the two neighbouring bent wood elements as a uniform line load over the length of each element in contact. This added a small additional dead load to those members to account for the wedge. The steel connection hardware (washers and nuts) was negligible in weight and ignored.

For snow, two cases were modelled: Uniform snow (based on a ground snow load of 0.85 kN/m^2 for Dresden, Zone 2), applied only to surfaces with slopes $\leq 70^\circ$, in line with Eurocode recommendations. In addition, asymmetric (drifted) snow, representing unbalanced accumulations with up to 2.0 times the uniform load applied to one side of the dome, depending on slope and orientation. Four drift directions (N, E, S, and W) were modelled as separate load cases.

Two wind directions were considered: 0° (front-to-back) and 90° (side-to-side). To apply wind loads realistically to the complex dome geometry, the bent wood elements were grouped into surface-based zones depending on their slope and orientation relative to the wind direction. *Figure 3* illustrates this classification for the case of wind from the west, showing how elements were grouped into belts or sectors across the dome. These element groups reflect different exposure conditions; from the windward base with positive pressure, through the side belts, up to the upper dome zone facing away from the wind, where suction dominates. The total wind force on each group was obtained by multiplying the respective pressure coefficient (based on Eurocode zones A–C) by the reference gust pressure and the horizontal projected area of the group. This total force was then distributed evenly across all beams in the group, proportional to their length, and applied as lateral line loads in the RFEM model. This approach ensured a differentiated and realistic representation of wind pressure across the dome. In particular, it accounted for changes in pressure due to curvature, enabling the identification of zones with high suction near the apex and positive pressure at the base, consistent with expected flow patterns over hemispherical structure.



Figure 3: Representation of the element groups of Wind loads

Pressure distributions were mapped to each beam based on orientation and slope. Slight adjustments in suction zones were included to reflect peak uplift slightly offset from the apex. Resulting forces were applied as lateral line loads to simulate realistic wind pressure behaviour. As an example, the nominal stress distribution of the model of the demonstrator with the frames with 40 mm thickness is presented in the *Figure 4*.



Figure 4: Nominal stress distribution of the demonstrator model

The analysis showed that certain members with the thickness of the 25 mm in the upper dome experience

bending moments that exceed the capacity under combined snow and wind. Increasing thickness to 40 mm in key areas or improving base anchoring improved capacity. The connectors themselves were not critical, both steel and densified wood dowels withstood the internal forces. This modelling confirms that the dome is stable and supports design loads. It also shows that the timber elements govern design, while the dowel joints offer sufficient performance if properly detailed.

4 – EXPERIMENTAL TESTS

The experimental phase includes three types of tests to evaluate the performance of the connections: bending, joint moment and shear (push-out) tests. Each test was conducted on specimens using the two connection types mentioned. All bent wood members were made from European beech with a cross-section of 25×100 mm (width × thickness). The steel connectors were M10 steel bolts (10 mm diameter) with washers and nuts (*Figure 5*, a). The CW dowels were made of densified beech wood with (compression ratio of 50% from it is original height) of 20 mm diameter (see *Figure 5*, b).



Figure 5: a) Steel bolt connection dimensions with diameter of 10 mm, b) CW dowel connection dimensions with diameter of 20 mm

In the wood connection, each dowel was secured by wooden wedges inserted into slotted dowel ends (an approach to expand and lock the dowel, similar to traditional dowel pinning). *Table 1* summarizes the test specimen configurations, including materials, geometry and number of specimens.

Table 1: An overview of the experiments					
Test Type	Number of	Board Length			
	Specifiens				
3-Point Bending	5 x CW dowel 5 x Steel bolts	1000			
Joint Moment	5 x CW dowel 5 x Steel bolts	500			
Shear	3 x CW dowel 3 x Steel bolts	500			

4.1. EXPERIMENTAL SETUP

4.1.1 THREE-POINT BENDING TEST SETUP

For the three-point bending test, each specimen consisted of two bent wood boards (length 1000 mm). The test

setup was a simply supported beam configuration with two supports and a central loading head (see *Figure 6*). The connected boards were placed with their ends on two supports and the loading piston located at mid-span. Several displacement transducers were installed to record deformations. Inductive linear variable displacement transducers (LVDTs) measured the mid-span deflection of the specimen as well as the relative slip between the two boards at the top of the joint (wedge region).



Figure 6: Three-point bending test; schematic and test setup photo

4.1.2 JOINT MOMENT TEST SETUP

In the second series, a joint bending test was performed to evaluate the moment capacity and rotational stiffness of the connection. This test was conducted in a four-point bending configuration on a frame-like specimen to create a nearly pure moment at the connection. Test arrangement is shown in *Figure 7*.



Figure 7: Joint moment test: schematic and experimental setup photo

Each specimen was composed of two bent wood members (length 500 mm) joined by the connector. Two equal loads were applied symmetrically at quarter-span points, so that the central joint region was subject to a bending moment and minimal shear. Two LVDTs were placed on either side of the connection (front and back) to measure the relative horizontal displacement between the two boards at the joint, which is directly related to the opening angle (rotation) of the connection. The average of the front and back measurements was used to determine the joint slip/rotation, eliminating any effects of slight asymmetry.

4.1.3 SHEAR (PUSH-OUT) TEST SETUP

The third series of tests subjected the connections to shear forces in a push-out configuration. Each shear test specimen consisted of a short assembly of two overlapping bent wood boards (length 500 mm) connected by dowels or bolts. The specimen was loaded in a shear frame such that one board was pushed relative to the other. In the machine, one end of the specimen was fixed and the other end was loaded parallel to the grain, introducing a shear force along the connector. The two boards were oriented at a slight angle during fabrication (~10° inclination of the joint plane) so that under load the force line would pass directly through the connector and the support, minimizing any moment in the connection. The schematic and image of the shear test is presented in *Figure 8*.



Figure 8: Shear test: schematic and experimental setup photo

4.2. EXPERIMENTAL RESULTS

The results of the experimental program are summarized in this section, with comparisons made between the CW dowel and steel bolt connections.

Bending Test Results: In the three-point bending test, both connection types exhibited almost identical capacities and behaviour. The average maximum load at failure was about 37-38 kN for both connections. The failure was governed by the bent wood boards themselves. In all bending tests, the failure mode was brittle tensile fracture of the wood in the lower part of the bent board. *Figure 9* shows the load-deflection diagram at mid-span, comparing the performance of CW dowel and bolt connections in the three-point bending test. Specimen B_D represents CW dowel connections, while B S corresponds to representative steel bolt connections.



Figure 9: Load-deformation diagram for mid-span deflection for comparison of dowel and bolt connections in three-point bending test

Joint (Moment) Test Results: The moment tests revealed significant differences between the CW and steel connections in terms of both strength and deformation capacity. The CW dowel connections achieved a higher average moment capacity (about 2.2 kN·m) compared to approximately 1.3 kN·m for the steel bolt connections. The load–deflection behaviour at mid-span for the joint moment test is presented in *Figure* 10. M_D denotes specimens with CW dowels, while M S refers to those with steel bolts.



Figure 10: Load-deflection diagram for comparison of CW dowel and bolt connections in joint moment test

While steel connectors are typically associated with higher load-bearing capacity, the test results indicated that CW dowels, when properly installed with wedges, could achieve substantial resistance. In the specimens with steel bolts, failure consistently occurred in the surrounding timber, not in the bolts themselves. The 10 mm diameter of the steel bolts resulted in localized bearing stresses that initiated cracks at the boltholes, leading to splitting of the bent wood members. The 20 mm wooden dowels distributed the load over a larger bearing area, which reduced stress concentrations and allowed the timber to carry higher loads before failure. These observations suggest that the steel bolts were not fully utilized, as their capacity exceeded that of the adjacent wood.

The CW dowel specimens exhibited more ductile behaviour, regardless of whether failure occurred due to dowel fracture or timber splitting. These connections showed gradual failure progression, with significant joint rotation and audible signs of wood compression preceding ultimate failure. The initial rotational stiffness was around 150-160 Nm/mrad for steel connections, compared to 45-50 Nm/mrad for dowel connections. This indicates that while the steel joints provide greater rigidity at small deformations, the wooden dowel joints offer higher energy absorption and rotational compliance under increasing loads.

Shear (Push-Out) Test Results: In the shear (push-out) tests, both connection types achieved very similar ultimate loads, but differences were noted in stiffness and failure characteristics. The maximum shear load for all specimens clustered tightly around 34 kN for both the CW and steel connections. *Figure 11* shows the load–deformation response in the shear test. S_D denotes CW dowel connections, S_S refers to steel bolt connections. This indicates the shear capacity was governed by the wood bearing/shear strength and not by the connector material. The failure modes provide insight: For the steel connections, every specimen failed by splitting of the wood boards in shear, parallel to grain. The 10 mm steel bolt remained essentially undamaged. In CW samples despite the sudden dowel fracture, it is important to note

that these occurred at load levels similar to the wood splitting cases, meaning the dowel's shear strength was well-matched to the wood's shear capacity.



Figure 11: Load-deformation diagram for the displacement of the frame boards for the comparison of CW dowel and bolt connections in Shear test

Table 2 presents a summary of key performance metrics for each test type including the maximum load or moment capacity for both connection types.

5 – CONCLUSIONS

This study investigated innovative adhesive-free timber connections using bent wood elements and compressed wood dowels, in comparison with traditional steel bolt connections. A comprehensive experimental program (bending, joint moment/rotation and shear tests) and numerical structural analysis were conducted. The following conclusions can be drawn:

The experimental investigations showed that CW dowel connections could provide structural performance comparable to traditional steel bolt connections in both bending and shear applications. While steel bolts offered greater initial stiffness and consistent behaviour across specimens, CW dowels exhibited higher rotational capacity and ductility, which can be beneficial for energy dissipation and joint flexibility in timber structures. The failure modes observed in dowel-connected specimens

Table 2: Summary of experimental results

Test Type	Specimen Code	Connection Type	Max Load	Moment Capacity
			[kN]	[kNm]
3-Point Bending Test	B_D	CW Dowel	37.68	8.48
	B_S	Steel Bolt	36.32	8.17
Joint Moment Test	M_D	CW Dowel	87.97	2.20
	M_S	Steel Bolt	52.13	1.30
Shear (Push-Out) Test	S_D	CW Dowel	34.09	-
	S_S	Steel Bolt	34.21	-

varied between failure in the wood and in the connector itself, indicating a balanced stress distribution. In contrast, failure in steel-connected specimens consistently occurred in the timber surrounding the bolts, with the steel components remaining largely unaffected, suggesting that the bolt strength exceeded the timber's capacity.

The comparison between the experimental results and the RFEM structural model confirmed that both the steel bolt and the CW dowel connections provide sufficient loadbearing capacity for the pavilion application. The ultimate internal forces predicted in the model were significantly lower than the failure loads observed in testing for both systems, indicating that either connection type meets strength requirements.

However, from a serviceability perspective, key differences emerged. While CW dowel connections offered higher deformation capacity and ductility, they also exhibited substantial initial rotation under load and lacked the stiffness required to maintain joint rigidity. These deformations could lead to joint opening and discomfort in a full-scale structure. In contrast, the steel bolt connections provided greater stiffness and more stable performance under service loads. The findings suggest that a combination of steel bolts and CW dowels can effectively combine the rigidity and consistency of steel connections with the ductility and reversibility offered by compressed wood. This hybrid approach supports the development of structurally efficient, low-impact and potentially demountable timber systems.

Future work may explore long-term behaviour (creep and moisture effects). The successful implementation in the demonstrator pavilion will serve as a proof-of-concept, inspiring more widespread use of all-timber connection technology in modern structural engineering.

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7 – **REFERENCES**

- D. Lordick, "BenDit A Polyhedral Sculpture from Bent Wood," in *Bridges 2021 Conference Proceedings*, 2021.
- [2] Z. Guan, A. Sotayo, M. Oudjene, I. El Houjeyri, A. Harte, S. Mehra, S. Namari, P. Haller, A. Makradi, S. Belouetter and F. Deneufbourg, "Development of adhesive free engineered wood products -Towards adhesive free timber buildings," in *World Conference on Timber Engineering (WCTE 2018)*, Soeul, Rep. of Korea, 2018.

- [3] DIN EN 1995-1-1, Eurocode 5: Bemessung und Konstruktion von Holzbauten Teil 1-1: Allgemeines - Allgemeine Regeln und Regeln für den Hochbau; Deutsche Fassung EN 1995-1-1:2004 + AC:2006 + A1:2008, Beuth Verlag, 2010.
- [4] J. Hartig, S. Namari, J. Wehsener and P. Haller, "Bemessung und experimentelle Untersuchungen von eingeschlitzten Verbindungen mit GFK-Platten und Stabdübeln für den Ingenieurholzbau," *Ernst & Sohn - Bautechnik 95*, vol. 11, 2018.
- [5] U. Mantau, H. Weimar, P. Döring and S. Glasenapp, "Rohstoffmonitoring Holz, Mengenmäßige Erfassung und Bilanzierung der Holzverwendung in Deutschland," Fachagentur Nachwachsende Rohstoffe e.V. (FNR), Rostock, 2018.
- [6] F. Kollmann, Technologie des Holzes und der Holzwerkstoffe, Heidelberg: Springer-Verlag, 1955.
- [7] W. C. Stevens and N. Turner, Wood bending handbook, Buckinghamshire: Fox Chapel publishing, 1970.
- [8] S. Namari, R. Qiang and P. Haller, "Experimental and Numerical Study on Adhesive Free Timber Constructions with Laminated Boards," in *Conference: World Conference on Timber Engineering (WCTE 2021)*, Santiago, Chile, 2021.
- [9] A. Kutnar, D. Sandberg and P. Haller, "Compressed and moulded wood from processing to products – a review," vol. 69, 2015.
- [10] D. Sandberg, P. Haller and P. Navi, "Thermohydro and thermo-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products," *Wood Material Science & Engineering*, vol. 8, pp. 64-88, 2012.
- [11] P. Navi and A. Pizzi, "Property changes in thermohydro-mechanical processing," Holzforschung, 2015.
- [12] S. Namari, L. Drosky, B. Pudlitz, P. Haller, A. Sotayo, D. Bradley, S. Mehra, C. O'Ceallaigh, A. Harte, I. El-Houjeyri, M. Oudjene and Z. Guan, "Mechanical properties of compressed wood," *Construction and Building Materials*, vol. 301, 2021.