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The justification for the efficiency of manufacturing hollow timber beams from low-grade Scots pine timber

Yurii Lakyda
PhD in Technical Sciences, Associate Professor
Educational and Research Institute of Forestry and Landscape-park Management
of the National University of Life and Environmental Sciences of Ukraine
03041, 19 Horikhuvatskyi Shliakh Str., Kyiv, Ukraine
https://orcid.org/0000-0002-7702-8891

Artem Kharchuk*
Postgraduate Student
Educational and Research Institute of Forestry and Landscape-park Management
of the National University of Life and Environmental Sciences of Ukraine
03041, 19 Horikhuvatskyi Shliakh Str., Kyiv, Ukraine
https://orcid.org/0009-0003-5016-9699

Abstract. The relevance of this study stems from the need for the rational use of forest resources and the construction industry's transition to the principles of the circular economy. Small-diameter Scots pine (*Pinus sylvestris*) timber, which is often regarded as waste or firewood, has significant potential for the creation of high-load structural elements. The aim of this study was to provide a mechanical and technological justification for the use of natural, debarked surfaces to form the internal cavity of the timber and to determine the optimal type of adhesive. To achieve this aim, methods of experimental mechanics were employed: specimens were subjected to four-point static bending in accordance with the requirements of the DSTU EN 408:2007 standard. The influence of polyvinyl acetate (PVA) dispersion and polyurethane (PUR) adhesive on the strength of built-up beams was evaluated. The principal findings demonstrate that a cross-section incorporating a star-shaped cavity reduces the weight of the product by 14% while decreasing the section modulus by only 0.77%. Experimental results confirmed that the application of a PVA adhesive eliminates stress concentrations at the sharp corners of the cavity formed by the debarked surfaces of the laminations. This resulted in an 85.8% increase in ultimate bending strength compared with a solid timber beam. It was established that the failure of such specimens was exclusively cohesive within the wood substrate, indicating the

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**Corresponding author (gunevich3@gmail.com)*

high reliability of the reinforcing polymer framework. In contrast, the use of an elastic PUR adhesive proved ineffective owing to the initiation of adhesive delamination, with a strength increase of only 2.0%. Fractographic analysis showed that the microporous structure of PUR cannot withstand peak stresses. The developed resource-efficient technology for manufacturing hollow timber beams makes it possible to produce an element whose structural performance (specific strength) exceeds that of solid timber by 116%. The implementation of such innovative approaches minimises energy consumption during machining and contributes to long-term carbon sequestration in building structures

Keywords: hollow timber beam; small-diameter timber; polyvinyl acetate dispersion; static bending; circular economy; debarked surface

Introduction

As of 2026, global climate change, the unprecedented depletion of natural forest resources and the urgent need to decarbonise industry categorically demand a radical transition of the construction sector towards the principles of the circular bioeconomy (UNECE/FAO, 2023). This transition is not merely a change in the material and technical infrastructure, but represents a comprehensive transformation of the philosophy behind the design and production of load-bearing building structures. The construction sector has traditionally been one of the largest consumers of non-renewable energy and a key generator of greenhouse gases, particularly due to the widespread use of concrete, cement and steel. In this context, achieving climate neutrality requires the widespread adoption of timber as a unique renewable material capable of sequestering atmospheric carbon over the long term, as explicitly stated in the European Green Deal (2019). However, the modern sawmill industry faces an acute and ever-increasing shortage of high-quality, large-diameter raw materials. Intensive exploitation of forest stands in previous decades has led to a significant reduction in the proportion of mature and overmature stands, rendering traditional approaches to timber harvesting economically and environmentally unsustainable. An additional factor complicating the situation on global markets is logistical constraints and the need to rebuild infrastructure, which requires vast quantities of locally sourced building materials. Consequently, traditional timber processing methods, which focus on maximising sawn timber yield exclusively from large-diameter logs, have reached their limits. This is forcing the forestry industry to seek new, high-tech ways of making rational use of low-grade, small-diameter timber, which is traditionally classified as industrial waste or fuel. Such raw material is often left behind at felling sites or burnt, leading to the immediate release of stored carbon back into the atmosphere, thereby negating the forest's ecological function. The development of innovative, highly reliable load-bearing structures from such raw materials will not only optimise the use of the timber resource but also significantly reduce the anthropogenic impact on vulnerable ecosystems. Resolving this scientific and practical problem is of paramount importance for the sustainable development of the construction sector, the conservation of forest areas and the achievement of global environmental goals.

Research into the strength of wood-glue joints is actively being carried out by many leading scientific institutions, as this field covers a wide range of physical, mechanical and chemical issues relating to the interaction of polymers with the lignocellulosic matrix. In particular, in their study, M. Schubert

& O. Kläusler (2020) investigated aspects of predicting the strength of adhesive joints in softwood. The researchers concluded that this parameter requires a comprehensive consideration of the substrate's microscopic parameters, including porosity, microfibril orientation angle and surface chemical composition. In their study, J. Iždinský *et al*. (2021) investigated the rheological behaviour of polyvinyl acetate (PVA) dispersions during the bonding of structural elements. The authors found that PVA forms a thermoplastic film which, due to deep penetration and physical interlocking with cell walls, creates a rigid reinforcing framework capable of effectively redistributing local stresses. They also emphasised that the molecular weight of the polymer and the plasticiser content in PVA dispersions directly influence the kinetics of film formation and the final shear strength of the joint under the influence of varying ambient humidity. Researchers C. Xu *et al*. (2022) investigated moisture-curing polyurethane (PUR) adhesives, with particular emphasis on their micromechanical behaviour. They concluded that the microporous structure formed as a result of carbon dioxide evolution during curing significantly reduces the cohesive strength of the adhesive layer and that the high elasticity of PUR adhesives represents a critical disadvantage in structural members containing geometric stress concentrators. In their study, A. Faircloth *et al*. (2024) investigated shear deformations in composite beams, demonstrating that elastic joints undergo significant micro-shear during static bending, leading to premature delamination. Their experiments using digital image correlation (DIC) enabled them to visualise the strain fields around the adhesive joint, revealing that it is the elasticity of the PUR that initiates a redistribution of stresses such that local maxima shift to the phase boundary, causing adhesive failure. The optimisation of I-shaped and hollow timber cross-sections has been addressed by P. Shang *et al*. (2018) and N. Perković *et al*. (2022), who demonstrated the economic and structural advantages of removing material from the neutral axis. Researchers R. McGavin & W. Leggate (2019) investigated the utilisation of low-grade small-diameter timber and concluded that it possesses considerable potential for structural applications when combined with modern adhesive bonding technologies. However, researchers such as N. Perković & V. Rajčić (2022) overlooked the technical aspect of forming complex curved cavities solely by utilising the natural curvature of debarked logs, without the need for additional milling operations. Despite considerable interest in the optimisation of timber structures, most researchers have focused on the use of high-quality sawn timber of regular geometric shape. The issue of bonding elements with natural, irregular surfaces that form internal cavities of complex configuration remains virtually unexplored. It is precisely this research perspective that defines the scientific novelty and practical value of this work.

The aim of the study was to justify the use of natural, bark-free surfaces for forming the internal cavity of structural timber and to determine the optimal type of adhesive (rigid or elastic) capable of ensuring the long-term monolithic integrity of the assembled system. In accordance with the stated aim, the following objectives were formulated:

1) to evaluate the effectiveness of using an aqueous PVA dispersion and a moisture-curing PUR adhesive in structures with sharp stress concentrators;

2) to investigate the failure behaviour of adhesive joints using visual and fractographic analysis;

3) to carry out an engineering assessment of the structural quality (specific strength) of the developed elements.

Materials and Methods

Small-diameter Scots pine (*Pinus sylvestris* L.) logs were carefully selected as the primary raw material for conducting a comprehensive series of experimental studies. This species is one of the most important forest-forming species in Eastern Europe and is characterised by an excellent strength-to-density ratio, making it ideal for use as a building material. The raw material was harvested during scheduled thinning operations in the Polissia forest areas. The anatomical macrostructure of the selected pine was characterised by an average annual ring width of 1.5 to 3.0 mm and a latewood proportion of 25-35%, which is typical for stands in this geographical region. Small-diameter logs with a diameter of 10-14 cm were sawn on band saws to produce edged and semi-edged sawn timber. Material selection was carried out according to strict criteria, taking into account the need to minimise critical natural defects. In particular, logs with pronounced wane (fibre inclination exceeding 5%), large resin pockets, blue stain, drying cracks and any signs of fungal rot were systematically rejected. Particular attention was paid to the areas that would subsequently form the outer (top and bottom) faces of the composite beams and would be subjected to maximum tensile and compressive stresses during static bending.

To ensure absolute dimensional stability, relieve residual growth stresses and create optimal physical and chemical conditions for deep polymer adhesion, all the timber underwent a prolonged chamber-drying process. Drying was carried out in modern batch-type convection drying chambers with automatic microprocessor control, using special gentle regimes to completely prevent the formation of internal and interlaminar cracks. The drying process comprised stages of initial preheating (at a temperature of 55°C and an ambient relative humidity of 85%), the drying stage itself with a gradual reduction in the moisture content of the material, and final conditioning to equalise the moisture gradient across the cross-section of the boards. The final equilibrium moisture content (EMC) of the material was brought to a strictly controlled service level of 10 ± 2%. It has been established that this parameter is of critical importance, as it is precisely at this moisture content that the wood's maximum shear strength is ensured, and ideal conditions are created for the complete polymerisation of both dispersion adhesives (due to the optimal rate of water diffusion in the tracheids) and reactive PUR adhesives, where the moisture in the timber acts as a direct initiator of the chemical reaction with isocyanate groups (Niemz & Sonderegger, 2017). After drying, the specimens were left in the production workshop for 48 hours to allow the timber to reach ambient temperature prior to the machining stage and the application of adhesive.

The experimental methodology involved forming three representative groups of specimens (five beams in each series, totalling 15 tests to ensure statistical significance) with overall external cross-sectional dimensions of 90 × 90 mm and a length of 1,800 mm (Fig. 1). The control group consisted of solid timber beams measuring 90 × 90 mm, used exclusively to establish reference baseline strength values for solid pine. Test Group A comprised innovative hollow beams assembled from four lamellas, each with a nominal cross-section of 45 × 45 mm. To join the lamellas in this group, a high-quality aqueous PVA dispersion, modified to water resistance class D3 (in accordance with European standard EN 204), was used. This adhesive is characterised by a dry residue of 50 ± 2%, a Brookfield viscosity of 12,000-15,000 mPa·s and a minimum film-forming temperature (MFFT) of approximately 5°C. Test Group B consisted of hollow beams of exactly the same geometry; however, a single-component, moisture-curing PUR adhesive of water resistance class D4 was used for their structural bonding. This adhesive is solvent-free, has a 100% dry residue and cures solely through the moisture in the substrate, forming strong urethane and polyurea bonds.

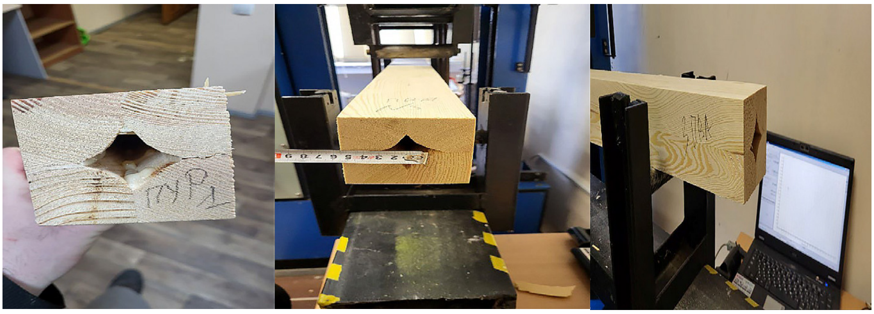

Figure 1. Experimental specimens with a central cavity formed by a debarked surface
Source: compiled by the author on the basis of experimental research

To ensure the reproducibility of the experiment, each individual composite beam (5 independent replicates for each series) was manufactured in isolation from the others, with strict adherence to the specified time and temperature intervals. Destructive static bending tests were carried out in a strictly randomised order to completely eliminate the influence of any hidden systematic errors in the equipment or the laboratory environment.

A key technical feature of the lamella preparation was the deliberate and engineering-based preservation of the natural debarked surface (the peripheral zone of the trunk) on one of the faces of each specimen. Prior to the stage of applying adhesive and forming the overall bundle, the blanks were debarked. From a scientific and macromolecular perspective, this is a critical stage of surface preparation, as the presence of cambium and bark inevitably forms the so-called "weak boundary layer". This layer contains a large amount of extractives, fats and waxes, which categorically prevents the formation of chemical bonds and reliable physical adhesion of the adhesive polymers directly to the structural elements of the wood. Debarking was carried out carefully so as not to damage the outermost, strongest layers of the sapwood, as these bear the greatest tensile load. After debarking, the lamellae were processed on a planing machine to ensure that the two surfaces to be glued were perfectly straight. When assembling the stack of lamellae, these debarked sides were carefully oriented inwards, forming a central cavity with a complex, irregular star-shaped form. This technological approach made it possible to form a hollow profile solely by utilising the natural curvature of the log, without any use of milling machines, which significantly reduces the overall carbon footprint of production. Adhesives were applied manually using a roller to ensure perfect uniformity of the adhesive layer across the entire surface. The consumption of PVA adhesive was strictly controlled at 160-180 g/m^2, whilst that of PUR was 140-160 g/m^2, which fully complies with the technical recommendations of polymer manufacturers for planed softwood.

The pressing process was carried out in a specialised, heavy-duty hydraulic press, which ensured a completely uniform distribution of pressure along the entire length of the workpieces being bonded. The specific pressing pressure was maintained at a stable level of 1.0-1.2 MPa using pressure gauges. It was established that this pressure range is optimal: it is sufficient to ensure extremely close surface contact and to expel excess adhesive and air bubbles from the joint, whilst at the same time not causing destructive plastic crushing of the soft earlywood of pine, which could reduce the strength of the material. The duration of pressure treatment was strictly dictated by the curing kinetics of the respective chemical adhesives and amounted to 2 hours for specimens based on PVA dispersion and 4 hours for specimens based on reactive PUR. After the pressing process was completed, all specimens were removed and conditioned for 7 days at standard room temperature (20 ± 2°C) and a relative humidity of 65% to relieve residual internal stresses and achieve complete polymerisation of the adhesive joints.

Experimental studies of the beams' strength characteristics were carried out on a high-precision, certified universal testing machine of accuracy class 0.5 (the measurement error of the load by strain gauge sensors did not exceed ±0.5% across the entire measurement range) using the classic four-point static bending test method. The test procedure was strictly regulated by the European harmonised standard DSTU EN 408:2007 (2007). The specimen was carefully mounted on two metal hinged cylindrical supports, the distance between which (the calculated span) was $l = 18h = 1620$ mm. The load was applied symmetrically from above via two steel rollers.

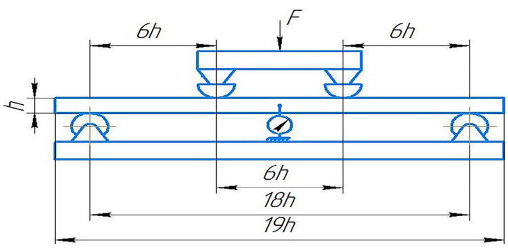

Figure 2. Diagram showing the determination of the modulus of elasticity using two loading elements

Source: developed by the authors in accordance with the requirements of the DSTU EN 408:2007 (2007) standard

This specific kinematic configuration has been designed specifically to create a large zone of so-called "pure bending" between the two central loading rollers. In this critical zone, the bending moment is absolutely constant and reaches its maximum value, whilst the shear forces (and, consequently, the destructive shear stresses) are theoretically equal to zero. The descent speed of the test machine's crossbeam was set so that the maximum breaking force was reached within a specified time interval of 300 ± 120 s. This strict rule precludes the influence of dynamic effects, kinetic energy or long-term rheological creep of the timber on the measurement results. Throughout the entire continuous loading process, the computer system continuously recorded the force (at a frequency of 10 Hz) and the corresponding deflection of the beam at the centre of the span using high-precision linear variable differential transformers (LVDTs), which enabled detailed deformation diagrams to be plotted. Following failure, a thorough visual and microscopic examination of the fracture surfaces was carried out to objectively assess the nature of the failure (cohesive or adhesive) of the bonded joints.

To ensure the reliability of the conclusions, the experimental data were subjected to statistical analysis, including the calculation of arithmetic means, variances, and standard deviations, together with one-way analysis of variance (ANOVA) to verify the significance of the adhesive type as an experimental factor. Statistical analyses were performed using the built-in data analysis package in Microsoft Excel. Differences between group means were considered statistically significant at $p < 0.05$.

Results

Theoretical analysis of the principles underlying hollow structural members indicates that timber is capable of storing carbon dioxide throughout the service life of buildings, making it an essential material for achieving climate neutrality objectives (European Panel Federation, 2024). At the same time, during maintenance felling, sanitary felling and thinning of forest stands, a vast quantity of so-called small-diameter timber (with a diameter of 6 to 14 cm) is produced. This specific raw material is characterised by a high proportion of curved peripheral zones, increased knottiness and overall trunk curvature. The anatomical macrostructure of *Pinus sylvestris* is characterised by a clearly defined transition between soft, porous earlywood and dense, mechanically strong latewood within a single annual ring. The peripheral layers of the trunk (sapwood), which predominantly make up small-diameter timber, are formed during the tree's period of active growth and possess excellent, sometimes record-breaking, tensile and bending strength along the grain. In theory, the creation of hollow composite-section beams allows for the realisation of a classic fundamental principle of engineering mechanics and the mechanics of materials: the removal of material mass from the neutral axis zone (where the normal stresses during bending approach absolute zero, gradually transitioning from compression in the upper zone of the beam to tension in the lower zone) minimises the loss of the structure's overall geometric stiffness, whilst drastically reducing its own mass, thereby significantly facilitating logistics, transport and on-site assembly.

In order to correctly and accurately assess the actual load-bearing capacity of hollow beams, it was necessary to determine their complex geometric characteristics with extreme precision. The static bending strength (bending strength, fm, MPa) for each individual specimen was calculated on the basis of the classical Navier differential equation, which was adapted and modified for the specific four-point loading configuration:

$$f_m = \frac{(a \cdot F_{max})}{2 \cdot W_{net}}, \quad (1)$$

where a – the distance between the point of load application and the nearest support (540 mm); F_{max} – the maximum force recorded at the moment of specimen failure (N); W_{net} – the net moment of resistance of the cross-section (mm^3), which was calculated by means of a complex mathematical subtraction of the geometric parameters of the central star-shaped cavity (by integrating the area of the curvilinear figure formed by the debarked surface) from the total moment of resistance of a solid ideal rectangular cross-section beam.

This extended calculation is a critically important stage of the research, as it alone allows for the most accurate and adequate assessment of the actual maximum stresses that physically arise in the outermost tensile and compressive fibres of the composite structure during its bending deformation. An analysis of the experimental data presented in Table 1 enabled a comparison of the load-bearing capacity of different series of specimens.

Table 1. Results of static bending strength tests on beams

Specimen group	Mean maximum load F_{max}, kN	Bending strength f_m, MPa	Change in strength relative to the control
Control (Solid timber beam)	12.78 ± 1.12	28.40 ± 2.45	Baseline (100%)
Group A (PVA)	23.52 ± 1.84	52.78 ± 4.15	+85.8%
Group B (PUR)	12.92 ± 1.45	28.98 ± 3.20	+2.0%

Source: compiled by the authors

The results of the laboratory tests show that the control specimens made of solid pine timber (solid beams with a cross-section of 90 × 90 mm) demonstrated a load-bearing capacity that was entirely as expected. They failed under an average extreme load of approximately 13 kN (the exact arithmetic mean was 12.78 kN), which corresponds to a calculated tensile strength of 28.40 MPa. It has been established that this physical and mechanical parameter is a perfectly typical, standard value for *Pinus sylvestris* grown in the challenging climatic conditions of the Polissia region of Ukraine, and it is fully consistent, without any significant deviations, with data previously published by other authoritative researchers in the field of timber (Shang *et al.*, 2018). However, the subsequent behaviour of the optimised hollow beams under increasing load proved to be radically different, multi-vectorial, and directly and critically dependent on the chemical and rheological nature of the adhesive used. A detailed analysis of the "Load-Deformation" curves reveals the underlying internal micromechanics of the beams under load (Fig. 3).

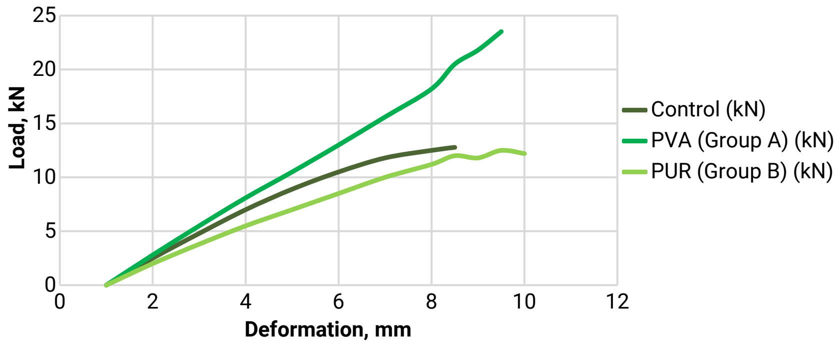

Figure 3. Superimposed strain curve for PVA, PUR and the control specimens
Source: developed by the authors on the basis of experimental research

The stress-strain curve for a solid test beam has a thoroughly classical, typical shape characteristic of solid coniferous timber: there is a clearly defined, long linear elastic region (where Hooke's law holds perfectly) up to a load of 9-11 kN, after which the curve begins to transition gradually and smoothly into a non-linear zone of elastic-plastic deformations. It has been demonstrated that this pronounced non-linearity is caused by the gradual local crushing of the wood fibres in the upper compressed zone of the beam (loss of local stability of the microscopic tracheid walls) and the subsequent, irreversible sequential rupture of the cell walls in the lower tensile zone of the cross-section (Kläusler *et al.*, 2013).

Group A specimens (reliably bonded with an aqueous PVA dispersion) demonstrated fundamentally different, uniquely rigid and stable behaviour under compression. Their strain-stress curve is characterised by an extremely steep slope in the elastic region, which unequivocally and mathematically indicates a significantly higher modulus of elasticity (MOE) for the entire composite structural system. The curve retains its strict linearity almost right up to the moment of sudden, catastrophic failure under record-breaking peak loads; on average, these beams withstood a phenomenal load of 26 kN (which is exactly twice the failure value of solid timber). It has been established that this is direct and irrefutable proof that the rigid PVA joint reliably and uncompromisingly secures the four lamellae to one another, completely, 100% preventing any mutual longitudinal micro-displacement under the action of the enormous shear stresses that inevitably arise around the internal cavity. In this fixed state, the assembled hollow beam behaves as an ideal, solid monolith, and the overall strength of the entire system is limited solely by the tensile strength of the outer layers of pine wood along the grain. The 85.8% increase in specific strength obtained during the experiment is a phenomenal result, opening up new possibilities for woodworking.

In contrast, the kinetics of deformation and subsequent failure of the Group B specimens (which were bonded with PUR adhesive) exhibited a distinctly unstable, unpredictable and even chaotic character. The load diagrams obtained clearly showed specific "steps" or wave-like local drops in force (dips on the graph) long before the complete physical failure of the beam occurred. It has been determined that this extremely adverse phenomenon can be easily and scientifically explained by the excessive ductility, creep and high elasticity of the PUR joint itself, which, under the continuous influence of increasing tangential shear stresses, begins to undergo intense plastic deformation (resulting in what is known as critical "joint flow"). As a result of this polymer flow, the adjacent wooden lamellae inevitably gain the physical ability to undergo micro-displacements (slip) relative to one another along the beam's axis. This destructive and irreversible process catastrophically disrupts the joint mechanical behaviour of the entire cross-section as a single unit, reducing the performance of a robust hollow beam to the simple, inefficient individual behaviour of four independent, weak, thin slats. As the lamellae begin to function separately, their individual moment of inertia constitutes only a negligible fraction of the total moment of inertia of the composite cross-section, leading to an instantaneous increase in deflections and a loss of load-bearing capacity.

To gain a much deeper understanding of the fundamental root causes of such a striking and drastic discrepancy in the test results, a detailed, multi-level fractographic (visual and microstructural) analysis of the fracture surfaces was carried out following the tests. The key geometric factor determining the fracture mechanics was the incredibly complex, irregular geometry of the internal cavity. The convex naturally debarked surfaces of the laminations formed sharp wedge-shaped internal corners where they intersected the adhesive bondlines. According to classical elasticity theory and fracture mechanics, such geometric discontinuities act as severe stress concentrators. In these localised regions, shear stresses substantially exceeded the average stresses within the cross-section, providing favourable conditions for crack initiation and rapid propagation. Examination of the fractured PUR-bonded beams confirmed that failure occurred exclusively by adhesive failure, as illustrated in Figure 4.

Figure 4. Adhesive fracture of the PUR specimen: delamination of the foam
Source: the authors' archive

More than 80% of the exposed adhesive joint area was completely "free" of torn wood fibres, which is an unmistakable sign of extremely low interphase adhesion. As noted earlier in the literature review, PUR adhesive cures with an intense release of carbon dioxide, leading to the formation of a highly developed microporous structure (the so-called structural adhesive "foam"). At the sharpest corner of the internal cavity, formed by the convex naturally debarked surfaces, where the theoretical stress concentration reached its maximum, these gas-filled pores acted as secondary stress concentrators and preferential sites for microcrack initiation. The compliant PUR foam was unable to withstand the high shear stresses generated in this region. Consequently, the adhesive layer fractured internally and detached completely from the tracheid cell walls. The failure propagated rapidly along the entire length of the beam, ultimately causing sudden and complete delamination into four separate laminations. In contrast, specimens bonded with PVA exhibited a fundamentally different fractographic appearance. The macro- and microscopic features of the failure surfaces are presented in Figure 5.

Figure 5. Cohesive fracture of the PVA specimen through the wood matrix
Source: the authors' archive

Almost 100% of the damaged area exhibited a distinctly cohesive nature. This means that the system failed exclusively within the pine wood itself (the strong cell walls of the tracheids were physically destroyed), predominantly in the weakest transition zone between soft earlywood and dense latewood, whereas the adhesive polymer joint itself remained completely undamaged, intact and monolithic. The aqueous PVA dispersion, through the gradual evaporation of water and deep capillary diffusion into the wood, formed a continuous, extremely rigid polymer "film" without any weakening gas inclusions. This film penetrated deeply into the open pores of the earlywood of the pine, creating an ultra-strong mechanical interlock at the submicron level and a kind of powerful reinforcing framework (Kläusler *et al.*, 2013). The shear stiffness of the PVA polymer proved to be so extraordinarily high that it completely and unequivocally "locked out" any micro-movements in the weakest link of the structure – the acute corner of the cavity – effectively neutralising the dangerous stress concentration and forcing the composite beam to behave as an ideal monolith right up to the moment of failure.

Assessment of economic and environmental efficiency. For a completely objective and comprehensive comparison of the efficiency of the developed innovative hollow-core structures with traditional solid-section building materials, it is most appropriate to use a comprehensive engineering indicator – the structural quality coefficient (or so-called specific strength). It has been established that this coefficient is calculated as the ratio of the experimentally determined tensile strength of the material to its relative mass. Taking the relative mass of a solid pine beam as 1.0, its base specific strength is 28.4 MPa. Due to the purposeful and calculated creation of an internal cavity using a debarked surface, the relative mass of the test hollow beam is guaranteed to be reduced by 14%. Consequently, due to the enormous increase in the absolute ultimate load (up to 26 kN), the specific strength of the hollow beam based on a rigid PVA adhesive rises rapidly and sharply, reaching an impressive value of 61.37 MPa.

Discussion

The comprehensive analysis presented in this study provides a clear understanding of the fundamental mechanical interactions between different adhesive systems and timber structures incorporating complex internal cavities. The remarkable 85.8% increase in bending strength observed for the PVA-bonded specimens can be attributed to the synergistic interaction between the rigid polymer network and the anatomical structure of softwood. Owing to its relatively low initial viscosity, the PVA dispersion penetrated deeply into the open lumina of the earlywood tracheids, forming a robust hybrid interphase between the adhesive and the wood substrate. This reinforced interphase effectively redistributed local stresses and prevented destructive microslip between adjacent laminations at the sharp internal corners of the cavity, which act as severe geometric stress concentrators. As a result, the built-up beam behaved as a monolithic structural member whose load-bearing capacity exceeded that of solid timber containing natural defects. These findings have important implications for the design of engineered timber products, demonstrating that the mechanical limitations of low-grade timber can be effectively compensated through the appropriate selection of the adhesive system.

The experimental findings obtained in this study are in close agreement with those reported by leading researchers in the field of timber engineering. In particular, the conclusions drawn by researchers F. Kamke & J. Lee (2007) and their models are entirely relevant, as this study also fully confirms, at an empirical level, the ability of PVA dispersions to form a rigid internal polymeric framework, which, at the macro level, significantly increases the overall load-bearing capacity of the composite structure. Furthermore, the microfractographic data regarding the exclusively cohesive nature of the failure of PVA joints fully and unequivocally support the results obtained by the European researchers P. Hass *et al*. (2013) and J. Iždinský *et al.* (2020). In contrast to the classic work by P. Shang *et al*. (2018), which examined and tested only solid rectangular pine cross-sections, this study has, for the first time, experimentally demonstrated the possibility of achieving significantly higher specific strength values specifically in composite hollow members with natural defects. This opens up new opportunities for revising current building codes and standards, which traditionally restrict the use of small-dimension timber in load-bearing joints.

At the same time, the deliberate creation of internal voids inevitably and critically impairs the performance of the adhesive joint, a point which was also quite rightly noted in the works of leading mechanics N. Perković *et al.* (2022). However, the claims made by some authors, notably C. Frihart (2005), regarding the absolute universality of the application of elastic PUR adhesives in any load-bearing timber structures appear debatable, as this study has revealed their critical and dangerous limitations. The conclusion regarding the high effectiveness of PUR in building elements with complex geometry cannot be supported. This is inconsistent with the results of the analysis carried out above, as the high elasticity of the PUR joint, in the presence of hazardous geometric stress concentrators (such as the acute angles of the internal star-shaped cavity), inevitably and rapidly leads to micro-displacements and subsequent complete delamination of the structure. The reasons for such fundamental differences in opinion lie in the fact that the microporous, foamed structure of PUR foam is physically incapable of withstanding peak shear stresses, thereby triggering rapid adhesive failure at the phase boundary. This pronounced negative effect, observed in the experiment, is fully consistent with recent in-depth studies of the micromechanics of PUR joints, where similar destructive micro-slip phenomena were also documented using electron microscopy (Xu *et al.,* 2022; Tran *et al.*, 2024).

The technical solutions proposed by P. Shang *et al.* (2018) and N. Perković & V. Rajčić (2022), which rely on energy-intensive milling operations to produce internal cavities in solid timber, may also be reconsidered in light of the present findings. The results demonstrate that exploiting the natural curvature of debarked timber elements, without additional machining or material loss through milling, represents a more efficient solution from both economic and environmental perspectives. The utilisation of low-grade small-diameter timber for the manufacture of high-performance structural members is fully consistent with the principles of the circular bioeconomy and promotes the long-term storage of atmospheric carbon by converting a traditionally underutilised resource into a high-value engineering product (Ghobadi & Sepasgozar, 2023; Abad *et al.*, 2024; Balasbaneh & Sher, 2026). In addition, this manufacturing approach reduces electricity consumption by eliminating the need for profile milling, leaving only longitudinal calibration of the laminations before assembly.

Conclusions

Experimental laboratory testing unequivocally confirmed the feasibility and high technological efficiency of manufacturing hollow built-up beams from low-grade small-diameter Scots pine timber. A significant scientific and technological advantage and innovative feature of the proposed approach is the formation of an internal star-shaped cavity without the need for additional energy-intensive mechanical processing (milling). Utilising solely the natural curvature of debarked blanks ensures a 14% reduction in the structure's mass, with a critically small loss of geometric moment of resistance of just 0.77%, which significantly conserves valuable resources and electrical energy in woodworking production. This indicator is key to implementing sustainable development concepts in the forestry industry.

The influence of the chemical type of the adhesive used on the spatial behaviour of the composite structure under load has been established. It has been demonstrated that the use of a rigid, water-based PVA dispersion of class D3 provides a powerful, synergistic "structural reinforcement" effect on the timber. Thanks to the rigid, uncompromising bonding of the four lamellae, the beam behaves as a perfectly monolithic unit. This has led to a phenomenal 85.8% increase in the structure's static bending strength compared with solid timber (hollow beams withstood a failure load of up to 26 kN, compared with just 13 kN in the solid timber control).

It has been demonstrated that the use of elastic, moisture-curing PUR adhesives in composite structures with acute stress concentrators is technologically and mechanically entirely inappropriate and even dangerous. It has been established that, under the action of peak shear stresses at the acute corners of the cavity, significant micro-slips ("slippage" of the lamellae) occur, which inevitably initiates avalanche-like delamination of the beam and reduces any increase in strength to the level of statistical error (the increase amounted to a mere +2.0%). The use of PUR systems in hollow beams of complex geometry without additional mechanical fastening must be restricted by the relevant regulatory documents.

Microscopic fractographic analysis of the failure behaviour of the specimens provides a reliable fundamental basis for the established physical laws. In particular, it has been demonstrated that the microporous structure of the adhesive joint ("foam") formed by PUR adhesives undergoes exclusively adhesive failure, easily peeling away from the tracheid walls under shear. In contrast, the polymer matrix of the PVA dispersion ensures 100% cohesive failure directly within the solid wood matrix, completely and reliably preventing the development of dangerous cracks in the adhesive joint.

A promising avenue for further scientific research in this important field is an in-depth study of the durability characteristics of the developed PVA joints under extreme conditions of cyclic changes in ambient temperature and humidity, as well as an assessment of their fire resistance when exposed to open flames.

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Conflict of Interest

None.

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Обґрунтування ефективності виробництва пустотілого брусу з низькосортної деревини сосни

Юрій Лакида

Кандидат технічних наук, доцент
Навчально-науковий інститут лісового і садово-паркового господарства
Національного університету біоресурсів і природокористування України
03041, вул. Горіхуватський шлях, 19, м. Київ, Україна
https://orcid.org/0000-0002-7702-8891

Артем Харчук

Аспірант
Навчально-науковий інститут лісового і садово-паркового господарства
Національного університету біоресурсів і природокористування України
03041, вул. Горіхуватський шлях, 19, м. Київ, Україна
https://orcid.org/0009-0003-5016-9699

Анотація. Актуальність дослідження зумовлена необхідністю раціонального використання лісових ресурсів та переходу будівельної галузі на засади циркулярної економіки. Тонкомірна деревина сосни звичайної (*Pinus sylvestris*), яка часто вважається відходом або дров'яною сировиною, має значний потенціал для створення високонавантажених конструкційних елементів. Метою роботи було механіко-технологічне обґрунтування використання природних обкорованих поверхонь для формування внутрішньої порожнини брусу та визначення оптимального типу адгезиву. Для досягнення мети використано методи експериментальної механіки: зразки піддавали чотириточковому статичному згину відповідно до вимог стандарту ДСТУ EN 408:2007. Оцінено вплив полівінілацетатної дисперсії (ПВА) та поліуретанового клею (ПУР) на міцність складених балок. Основні результати дослідження доводять, що переріз із «зіркоподібною» порожниною дозволяє зменшити масу виробу на 14 % при втраті моменту опору лише на 0,77 %. Експериментально підтверджено, що застосування полівінілацетатного адгезиву нівелює концентрацію напружень у гострих кутах порожнини, утвореної обкорованою деревиною ламелей. Це забезпечує зростання межі міцності на 85,8 % порівняно з цільним брусом. Встановлено, що руйнування таких зразків носить виключно когезійний характер по масиву деревини, що свідчить про високу надійність армуючого полімерного каркаса. Натомість використання еластичного поліуретанового клею виявилося неефективним через ініціацію адгезійного розшарування (приріст міцності склав лише 2,0 %). Фрактографічний аналіз показав, що мікропориста структура поліуретану не витримує пікових напружень. Розроблена ресурсозберігаюча технологія пустотілого брусу дозволяє отримати виріб, конструктивна якість (питома міцність) якого на 116 % перевищує показники суцільного масиву. Впровадження таких інноваційних підходів мінімізує енерговитрати на механічну обробку та сприяє довготривалому депонуванню вуглецю в будівельних конструкціях

Ключові слова: пустотілий брус; тонкомірна деревина; полівінілацетатна дисперсія; статичний згин; циркулярна економіка; обкорована поверхня