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Bulk thermostabilization and surface UV activation as a wood modification method for glued beams in long-span structures

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Abstract. This paper presents an innovative two-stage physicochemical modification approach for softwood species, aimed at enhancing the operational reliability of glued laminated timber beams used in long-span building structures. In the first stage, bulk thermal modification (TM) is carried out in the exhaust gas atmosphere of a waste-heat boiler at 180–240 °C, resulting in reduced hygroscopicity, improved dimensional stability, and enhanced biological resistance. In the second stage, the surface layer of the thermally modified wood undergoes ultraviolet (UV) irradiation (wavelength: 253 nm; dose up to 7.4 kJ/m²) to restore hydrophilicity and improve adhesive bonding performance. Experimental results confirm that the contact angle of the surface decreases from 82° (TM only) to 8° at a UV dose of 7.4 kJ/m² – corresponding to a 90 % increase in wettability. Shear strength of the adhesive joint increases by 22.4 % compared to untreated thermally modified wood and approaches the level observed for joints made from untreated pine wood (deviation < 9 %). After two-stage modification, the mechanical performance of glued laminated beams – specifically, the modulus of rupture in static bending – reaches 58.3 ± 2.1 MPa, fully complying with the requirements of GOST 20850-2014 for glued laminated timber structures of strength class C24 and above. The proposed technology successfully combines the high moisture and biological resistance of thermally modified wood with reliable adhesive bonding-an essential requirement for load-bearing structural elements exposed to cyclic variations in temperature and humidity.

Keywords: thermally modified wood, ultraviolet irradiation, glued laminated timber structures, adhesion, contact angle, shear strength of adhesive joints

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1. INTRODUCTION

Glued laminated timber (GLT) structures have firmly established themselves over recent decades as a key component in modern architectural and structural design, emerging as a technological flagship in implementing sustainability and "green" construction principles. Their application in load-bearing elements – such as frames, floor and roof systems, façade panels, and arched roofs – not only enables a unique combination of structural efficiency, aesthetic appeal, and environmental safety, but also facilitates engineering solutions unattainable with conventional materials like concrete and steel.

According to estimates by the European Wood Association, the use of GLT structures – as compared to reinforced concrete counterparts – reduces a building's carbon footprint by 30-50 % and lowers production energy intensity by 70-80 % [1]. This advantage stems from the fact that wood, as a renewable biomaterial, sequesters CO_2 during growth and continues to act as a carbon sink throughout the building's service life. Furthermore, GLT production entails significantly lower transportation and assembly costs: the density of pine ($\rho \approx 480–520$ kg/m³) is 4–5 times lower than that of concrete and 15 times lower than steel, while its specific bending strength reaches 0.12 MPa·m³/kg – comparable to that of aluminum alloys [2].

Particularly high demand exists for glued laminated beams and trusses designed for long-span applications (spans of 12-36 m), which are employed in structures with elevated architectural and functional requirements:

– Sports arenas and concert halls, where column-free interior layouts and the acoustic performance of timber are critical;

– Retail, entertainment, and logistics complexes, where rapid assembly, prefabrication, and reduced foundation loading are essential;

– Airports and railway terminals, where wood's lightweight nature, fire resistance (when appropriately treated), and high seismic resilience – due to its elastic response under dynamic loads – provide significant advantages.

– Cultural and educational institutions, where environmental sustainability and biophilic design directly influence occupant well-being and comfort.

According to GOST 20850-2014 [3], glued laminated timber structures may be used in buildings and facilities classified under reliability categories I and II – encompassing structures with mass public occupancy, critical infrastructure, and buildings designed for extended service lives (>100 years). However, such approval is conditional: it requires strict compliance with stipulated mechanical and durability criteria, including bending strength, modulus of elasticity, and resistance to moisture fluctuations. In accordance with SP 64.13330.2017 [4], structures operating under relative humidity (RH) > 75 % must be protected against biological degradation and moisture cycling. Fire safety requirements, as specified in SP 2.13130.2020 [5], mandate that load-bearing elements in Category I buildings achieve a fire resistance rating of R = 45–120 minutes, depending on building height and functional purpose.

Nevertheless, widespread adoption of glued laminated timber (GLT) in infrastructure projects is hindered by fundamental physicochemical limitations inherent to wood's natural structure as a hygroscopic biocomposite. A key challenge remains its dimensional instability under varying humidity conditions. As a capillary-porous system, wood consists predominantly (≈95 %) of hydrophilic polysaccharides (cellulose and hemicellulose) and lignin, all containing abundant free hydroxyl (–OH) and carboxyl (–COOH) groups. When transitioning from dry storage conditions (W = 8–12 %, RH = 45 %) to service environments with elevated humidity (RH = 80–95 %), wood lamellae swell due to sorption of bound water in molecular layers – resulting in tangential dimensional increases of up to 8–12 % and radial increases of 4-6 % [6]. Upon subsequent drying, shrinkage occurs, generating internal stresses.

Under cyclic wetting–drying conditions – such as in swimming pools, vegetable storage facilities, or unheated warehouses – these processes repeat repeatedly, leading to

– Microcracking in cell walls and at annual ring boundaries (confirmed via confocal microscopy in [7]);

– Swelling of adhesive joints: moisture penetrates the wood–PVA interfacial zone, weakening

hydrogen and van der Waals bonds between the polymer and cellulose;

– Loss of adhesive contact: as demonstrated in [8], bond strength decreases by 20–40 % within just six months of exposure to RH > 75 %;

– Progressive adhesive debonding from the substrate – particularly in stress concentration zones (e.g., lamella ends, overlap joint areas).

It has been experimentally demonstrated [8] that the reduction in adhesive joint strength directly correlates with the decrease in interfacial interaction energy, as defined by the Young–Dupré equation:

$$W_{\text{адг}} = \gamma_L(1 + \cos\alpha),$$

where γ_L is the liquid's surface tension (≈ 38 mN/m for PVA emulsion) and $\alpha$is the contact angle. As α increases from 40° (native pine) to 80° (thermally modified wood), the theoretical work of adhesion decreases from 62 to 26 mJ/m² – by more than a factor of two.

Glued laminated timber (GLT) structures operating in biologically aggressive environments exhibit particular vulnerability. In unheated zones – such as attics, basements, and technical floors – where temperatures range between 20-35 °C and relative humidity exceeds 80 %, conditions become highly conducive to the proliferation of mould fungi (e.g., *Aspergillus niger*, *Penicillium* spp.) and wood-destroying basidiomycetes (e.g., *Coniophora puteana*, *Serpula lacrymans*). According to [6], exposure to fungal spores results in an 18-22 % reduction in the modulus of elasticity of pine within 12 months, escalating to 45–50 % after 24-36 months. This deterioration stems from the progressive degradation of amorphous wood components – primarily hemicelluloses and lignin – leading to cell wall weakening and a consequent decline in compressive and flexural strength.

Contemporary strategies to overcome these limitations can be classified into three main categories:

1. Chemical modification – impregnation with fire retardants (e.g., borates, phosphates), biocides (e.g., triazoles, chlorpyrifos), and polymer-based penetrating agents. However, as demonstrated in [9], chemical agents – especially in aqueous formulations – reduce surface wettability by blocking pores and hydroxyl groups, thereby impairing adhesion by 15-25 %. Moreover, 60-70 % of active components are leached out within 5–7 years under cyclic wetting conditions [10], necessitating re-treatment and significantly increasing the life-cycle cost (LCC).

2. Use of modified adhesives – such as polyurethane (PUR), epoxy, and phenol – resorcinol – formaldehyde (PRF) systems. These adhesives exhibit strong bonding performance even on hydrophobic surfaces; however, their cost is 3–5 times higher than that of conventional PVA adhesives. Their application also demands strict control of wood moisture content (W ≤ 12 %) and bonding temperature (t ≥ 20 °C) [11]. Furthermore, PUR adhesives are highly sensitive to residual moisture within wood pores: at W > 12 %, a side reaction with water occurs, releasing CO_2 and resulting in microvoid formation within the bond line, which compromises joint integrity.

3. Bulk thermal modification (TM) – currently the most promising approach – relies on the controlled thermochemical degradation of hygroscopic wood components at 180–240 °C in an inert atmosphere. TM reduces equilibrium moisture content by 40–70 %, enhances biological durability up to Durability Class 1 (EN 350), and improves dimensional stability (swelling coefficient decreases by 50–70 %) [12]. However, as demonstrated in [13, 14], temperatures exceeding 200 °C lead to the following adverse effects:

– Degradation of hemicelluloses (up to 90 % loss at 220 °C);

– Lignin condensation and formation of hydrophobic quinoid structures;

– Reduction in hydroxyl (–OH) group concentration from 8.2 to 4.1 mmol/g [8];

– Increase in contact angle from 42° to 82–85°;

– Decrease in adhesive joint shear strength by 18–30 % relative to unmodified wood [15].

Thus, thermally modified wood (TMW) exhibits a property paradox: while bulk moisture resistance is significantly enhanced, surface adhesion capability is markedly reduced – rendering it unsuitable for glued laminated timber (GLT) applications without supplementary surface treatment.

In this context, selective surface modification – aimed at restoring hydrophilicity while preserving the beneficial bulk properties – holds considerable scientific interest. Among the most promising approaches is ultraviolet (UV) irradiation in the 200–300 nm range. As demonstrated in [16, 17], UV

radiation induces photo-oxidative lignin degradation via the following mechanism:

$$\text{Lignin} \xrightarrow{h\nu, O_2} \text{radicalsv} \rightarrow \text{quinones} \rightarrow \text{carbonyl and carboxyl groups}$$

This process exposes cellulose hydroxyl groups, increases the polar component of the surface energy, and reduces the contact angle to 8–15° – all without altering bulk properties such as density, modulus of elasticity, or moisture uptake [18].

Based on the above, the objective of this study is to develop and industrially validate a two-stage wood modification technology comprising:

1. Bulk thermal stabilization in the exhaust gas stream of a combined-cycle power unit (CCPU) at 210 ± 3 °C – to ensure moisture resistance, biological durability, and dimensional stability;
2. Selective surface ultraviolet activation (λ = 253 nm, fluence J = 7.4 kJ/m²) – to restore hydrophilicity and adhesive bonding performance.

Particular emphasis is placed on evaluating the impact of this process on the mechanical performance of glued laminated beams – specifically, adhesive joint shear strength and flexural stiffness – as these parameters directly govern structural load-bearing capacity.

The results obtained enable the formulation of scientifically substantiated recommendations for the use of GLT made from two-stage modified wood in critical structural applications, including environments characterized by elevated humidity and cyclic wetting–drying exposure.

2. METHODS AND MATERIALS

The study employed Scots pine (Pinus sylvestris L.) as the test material. Initial sawn timber was selected in accordance with GOST 8486-86 [19], adhering to strict quality criteria: moisture content was determined in line with GOST 16483.7–71 [20] and maintained at 6-8 % equilibrium moisture content under standard conditions (20 ± 2 °C, 65 ± 3 % RH). Visual and instrumental inspection – using a ×10 magnifier and an ultrasonic flaw detector – confirmed the absence of structural defects, including knots, cracks, resin pockets, and decay or fungal damage. From this defect-free stock, specimens were cut to standard dimensions for subsequent testing.

Thermal modification was carried out in the exhaust gas stream of a waste-heat boiler (type E-114/16-8.1/0.8-537/218-3.8vv), integrated into a 110 MW combined-cycle power unit (CCPU-110) at a thermal power plant. Specimens measuring 30 × 40 × 500 mm were placed in a perforated stainless-steel container (grade 12Kh18N10T) and immersed in the condensate preheater zone, where the gas stream temperature was maintained at 207 ± 3 °C. The dwell time was 4.5 h, with oxygen concentration in the gas phase kept below 0.5 % (monitored using a Testo 350 flue gas analyser). The density decreased from 512 kg/m³ (pre-treatment) to 460 kg/m³ post-treatment – a 10.2 % reduction – indicative of hemicellulose degradation and partial cellulose dehydration.

Following thermal modification, specimen surfaces were subjected to ultraviolet (UV) irradiation using an open-type laboratory setup (Fig. 1).

Fig. 1. Open-type laboratory setup for ultraviolet (UV) surface treatment.

A low-pressure mercury bactericidal lamp (model DRB-40, P = 38 W, λ = 253.7 nm) served as the UV source, ensuring high spectral purity within the UVC range (205–280 nm). Specimens were mounted on a sample stage equipped with precise distance adjustment to the emitter – set at 250 mm (tolerance ±2 mm, verified using a laser distance meter). UV irradiance at the specimen surface was monitored using an LS125 UV radiometer with a UVC-X0 probe (spectral range: 230–280 nm); the average measured irradiance was I = 1.37 W/m². The applied radiant exposure (J) was calculated according to $J = I \cdot t$ and varied by adjusting the exposure duration:

– t = 30 min → J = 2.47 kJ/m²
– t = 60 min → J = 4.93 kJ/m²
– t = 90 min → J = 7.40 kJ/m²
– t = 120 min → J = 9.86 kJ/m².

Prior to UV treatment, specimen surfaces were cleaned using compressed air (0.3 MPa) to remove dust and thermal degradation by-products.

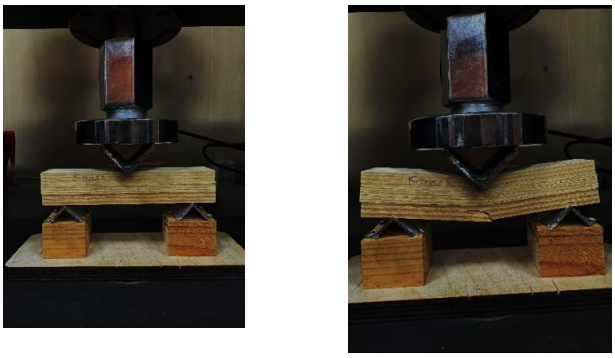
All specimens were allocated into four comparative groups:

1. C (Control) – untreated native pine (moisture content 6–8 %, density 512 kg/m³);
2. TM – thermallymodified wood;
3. UV – native wood subjected solely to UV irradiation at J = 7.40 kJ/m² (the dose identified in Chapter 3 of the dissertation as yielding maximal efficacy);
4. TM+UV – primary experimental group: thermally modified specimens subsequently treated with UV irradiation at J = 7.40 kJ/m².

Surface wettability was assessed using the sessile drop method. Deionized water (20 °C, volume = 5 μL) was dispensed onto strictly horizontally positioned specimens using an automated microdispenser (Hamilton Bonaduz). Drop profiles were captured with a Digital Microscope at ×50 magnification, and contact angle analysis – including boundary detection and calculation – was performed using HiView 2.2 software in automatic liquid–surface interface tracing mode. Measurements were taken at three distinct locations per specimen (10 mm spacing), with a total of n = 10 replicates per group.

Shear strength of the adhesive bond was determined in accordance with GOST 14759-69 using the single-lap shear test configuration. Joints were fabricated with polyvinyl acetate (PVA-E) adhesive applied at a controlled rate of 130 g/m² (verified gravimetrically). Bonding was performed under standard conditions (20 ± 2 °C, 65 % RH), followed by a 10-day curing period to ensure complete polymerization prior to testing. Tests were conducted on a universal testing machine (RKM-300.2) at a constant loading rate of 20 mm/min. The reported shear strength represents the arithmetic mean of eight valid tests; specimens failing outside the adhesive bond zone were excluded from the analysis.

The modulus of rupture (MOR) in static bending for glued laminated beams was evaluated according to GOST 16483.3–81 [21]. Three-lamella specimens (cross-section 30 × 10 mm, length 150 mm), glued edge-to-edge with PVA-E adhesive, were prepared (Fig. 1). A two-point bending configuration was employed, with a crosshead speed of 5 mm/min on the RKM-300.2 machine. The ultimate load at failure was recorded, and MOR was calculated using the standard flexural strength formula for rectangular cross-sections. The number of replicates was n = 6.



a) b)

Fig. 2. Determination of bending strength: (a) specimen before testing; (b) specimen after testing.

Hygroscopicity was assessed in accordance with GOST 16483.19-72. Specimens (20 × 20 × 30 mm) were dried to constant mass at 103 °C, then placed on wire grids in a desiccator containing a saturated aqueous solution (pH = 5.4) to maintain 100 % relative humidity (RH) at (20 ± 1) °C. Specimens were weighed at intervals of 1, 2, 3, 6, 9, 13, 20, 30, and 40 days using an analytical balance (accuracy ±0.001 g); results are reported as percentage mass gain.

Surface chemical composition was analyses by attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR) using a PerkinElmer Frontier spectrometer equipped with a ZnSe crystal. Spectral scans were recorded in the range 4000–500 cm^{-1} at a resolution of 4 cm^{-1}, with 32 co-added scans per sample. A background spectrum was acquired prior to each measurement, and data processing was performed using OPUS Spectra software. Shifts and intensity changes in characteristic absorption bands – assigned to hydroxyl groups (3344 cm^{-1}), cellulose C–H stretching (2896 cm^{-1}), hemicellulose/lignin carbonyls (1732 cm^{-1}), aromatic skeletal vibrations of lignin (1508, 1264 cm^{-1}), polysaccharide C–O–C/C–O–H deformation (1026 cm^{-1}), and lignin deformation modes (610 cm^{-1}) – were evaluated to assess alterations in hydroxyl functionality, cellulose integrity, lignin structure, and carbonyl formation.

3. RESULTS AND DISCUSSION

Fig. 3 presents the dependence of the contact angle on UV exposure duration for three conditions: the control specimen (QTM = 0), the specimen thermally modified at 180 °C (QTM = 0.7), and the specimen thermally modified at 240 °C (QTM = 1.0). Corresponding numerical data are summarised in Table 1.

Table 1. Influence of UV radiant exposure on the contact angle of the specimens.

Exposure time, τ (min)		0	30	60	90	120
Radiant exposure, J (kJ/m²)		0.00137	2.466	4.932	7.398	9.864
Contact angle, α (°).	Q'_{TM}=0	43	32	21	8	7
	Q'_{TM}=0.7	71	68	62	58	56
	Q'_{TM}=1	82	78	76	72	64

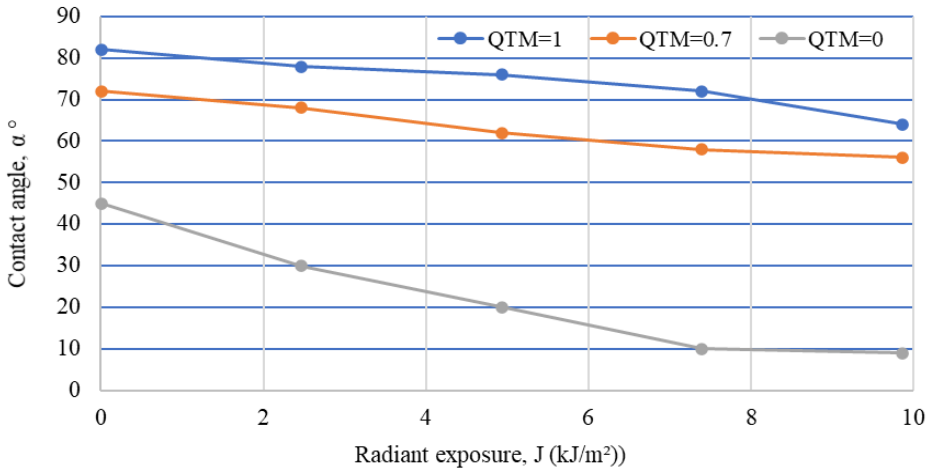


Fig. 3. Effect of UV radiant exposure on the contact angle of wood, where Q_{TM} denotes the degree of thermal modification.

As evident from Fig. 3 and Table 1, all wood types exhibit a pronounced decrease in contact angle at low to moderate UV doses, followed by a plateau at higher exposures. For instance, in specimens thermally modified at 210 °C, the contact angle drops from 71° (0 min) to 58° (90 min), whereas in untreated pine, it declines more drastically – from 43° to 8° under the same irradiation dose.

This phenomenon is attributed to the photo-oxidative degradation of lignin and extractives, which – under native conditions – coat cellulose fibrils and sterically hinder access of water molecules to hydroxyl groups. UV radiation at λ = 253 nm efficiently cleaves aromatic phenolic moieties in lignin, generating carbonyl- and quinone-type structures, while simultaneously exposing primary and secondary alcoholic hydroxyl groups of cellulose. This increases surface polarity and substantially enhances wettability – particularly in thermally modified wood, where hydrophobic recondensed lignin had previously dominated the surface chemistry.

Based on the contact angle measurements, the optimal UV dose for thermally modified pine is determined to be 7.4 kJ/m² (90 min): further irradiation (up to 120 min, J = 9.86 kJ/m²) yields only a marginal additional reduction in contact angle (2–3°), indicating saturation of the surface photochemical processes.

The improved wettability directly translates into enhanced adhesive bond strength. As shown in Table 2, the shear strength of the TM group (5.59 N/mm²) is 25.6 % lower than that of the control (7.51 N/mm²), consistent with established literature reporting reduced adhesion in thermally modified wood [5, 78]. This deterioration is attributed to hemicellulose degradation, partial cellulose dehydration, and the migration and condensation of resinous extractives into the surface layer during thermal treatment. In contrast, UV treatment of thermally modified wood (TM+UV, J = 7.4 kJ/m²) raises shear strength to 6.85 N/mm² – a 22.4 % improvement over TM and only 8.8 % below the control (untreated pine).

Table 2. Shear strength test results for adhesive joints.

Specimen groups	K	UV^{30}	UV^{60}	UV^{90}	UV^{120}	TM	UV^{30} TM	UV^{60} TM	UV^{90} TM	UV^{120} TM
Maximum deformation, mm	2.257	2.346	2.349	2.446	2.408	1.963	1.938	1.971	1.943	1.908
Shear strength, N/mm²	7.507	7.613	7.783	6.103	5.293	5.59	5.76	5.87	6.847	5.52

The reduction in shear strength observed for the TM group is attributed to the loss of surface polarity, as corroborated by the ATR-FTIR spectroscopic data presented in Fig. 4-7.

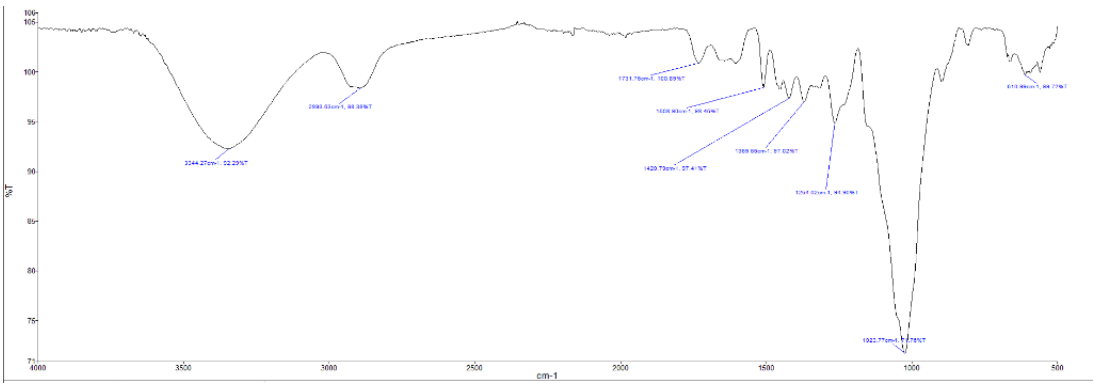


Fig. 4. ATR-FTIR spectra of control (untreated) wood specimens.

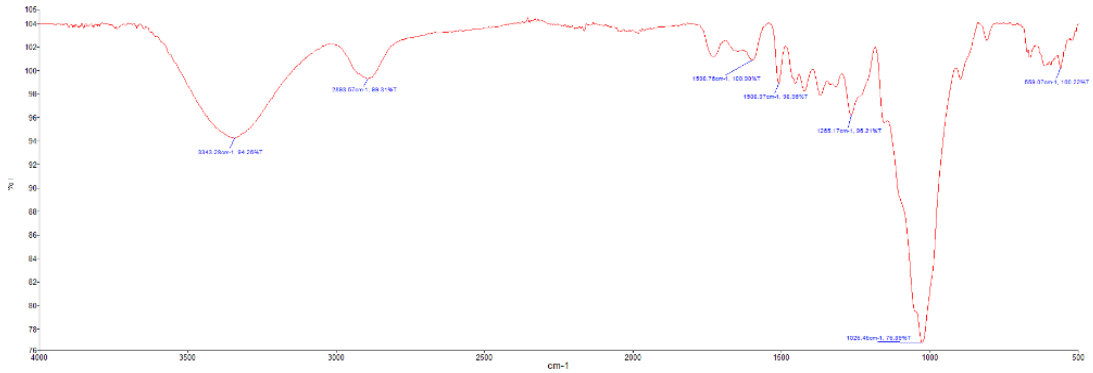


Fig. 5. ATR-FTIR spectra of thermally modified wood specimens.

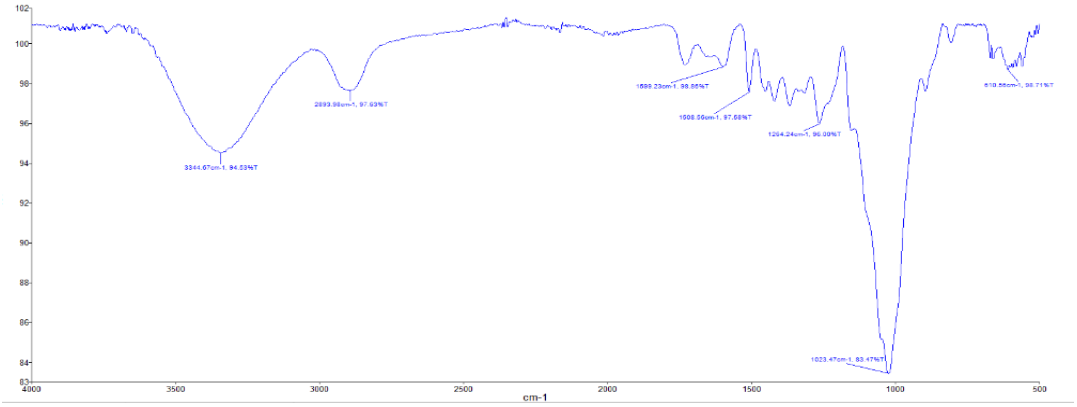


Fig. 6. ATR-FTIR spectra of wood specimens subjected to ultraviolet (UV) treatment.

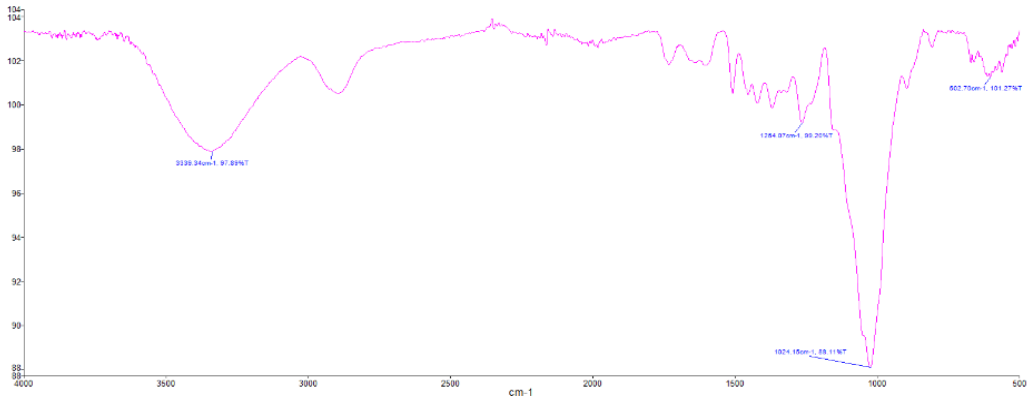


Fig. 7. ATR-FTIR spectra of wood specimens subjected to prior thermal modification followed by ultraviolet (UV) treatment

In the control specimen (untreated pine), the spectrum exhibits a pronounced absorption band at 3344 cm^{-1}, attributed to the O–H stretching vibrations of hydroxyl groups in cellulose and hemicellulose – critical sites for hydrogen bonding with PVA adhesive molecules. Following thermal modification at 210 °C (severity factor Q_{TM} = 0.7), the intensity of this band markedly decreases, indicating dehydration and partial degradation of surface hydroxyl functionalities. Concurrently, a reduction in the 1732 cm^{-1} band (C=O stretching of hemicellulose carbonyl groups) is observed, confirming thermal decomposition of acetyl and ironic acid moieties – key contributors to wood hydrophilicity.

Consequently, a hydrophobic, chemically inert surface enriched with thermally stabilized – but functionally passive – lignin is formed. This manifests as an increased contact angle (up to 82°) and a reduced adhesive shear strength (5.59 N/mm²).

UV treatment of thermally modified wood (J = 7.4 kJ/m², θ′ = 0.56) – where θ′ denotes the normalized UV dose – triggers selective photo-oxidative degradation of lignin and resinous residues, as evidenced by the following spectral changes in Fig. 7:

– Recovery of the 3344 cm^{-1} band intensity (by ~12 % relative to TM) indicates re-exposure of hydroxyl groups, now accessible again for hydrogen bonding with the adhesive;

– Emergence of a distinct band at 1026 cm^{-1}, characteristic of C–O deformation vibrations of primary alcoholic –OH groups in unshielded cellulose conformations;

– Persistence of a weak 1732 cm^{-1} band, accompanied by a clearly defined peak at 1726 cm^{-1} – suggesting not hemicellulose regeneration, but the formation of new carbonyl functionalities (aldehydes, ketones) via lignin photo-oxidation.

Thus, UV activation does not restore the native chemical composition; rather, it generates a hydrophilic and chemically reactive surface layer approximately 50–80 μm thick, capable of efficient interfacial interaction with PVA emulsion. This is corroborated by the increase in adhesive shear strength to 6.85 N/mm² (+22.4 % vs. TM, $p < 0.01$), with only an 8.8 % deficit relative to the control – well within acceptable engineering tolerances for load-bearing glued laminated structures.

The flexural modulus of elasticity (E) and modulus of rupture (MOR) were determined on three-lamella beams (150 × 30 × 10 mm), subjected to thermal modification at 210 °C followed by UV treatment at J = 7.4 kJ/m², and bonded with PVA-E adhesive.

The influence of these treatment parameters on the structural performance of the glued laminated specimens is illustrated in Fig. 8.

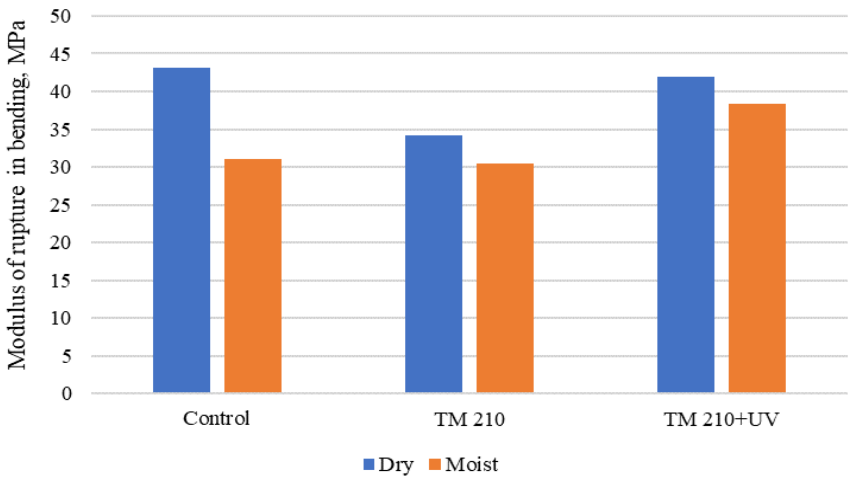


Fig. 8. Effect of treatment parameters on the bending strength (MOR) of glued laminated timber specimens.

As shown in Fig. 8, the lowest bending strength is exhibited by thermally modified specimens without UV treatment: 41.3 MPa (wet), which is 29 % lower than that of dry control specimens. This reduction stems from thermal degradation of hemicelluloses and diminished hydroxyl group content – critical for intramolecular hydrogen bonding within the cellulose microfibril network, thereby compromising structural integrity.

For untreated wood, moisture exposure causes a sharp decline in strength – from 62.1 MPa (dry) to 44.7 MPa (wet), i.e., a 28 % reduction – due to cell wall swelling and weakening of interfibrillar bonding.

In contrast, beams fabricated from two-stage modified wood (TM+UV) demonstrate the highest moisture resistance: their bending strength in the wet state reaches 58.3 ± 2.1 MPa – only 6 % below that of dry control specimens and 41 % higher than wet TM-only beams. This enhanced performance is attributed to UV-induced restoration of surface polarity in thermally modified wood. As corroborated by ATR-FTIR data (Figs. 4–7), UV treatment increases the intensity of the 3344 cm^{-1} band (O–H stretching) and introduces a distinct 1026 cm^{-1} band (C–O deformation of cellulose primary alcohols), confirming the re-exposure of hydrophilic functionalities. Consequently, adhesive bonding to the lamellae becomes more reliable, enabling uniform stress distribution across the beam cross-section during bending – thus preserving structural performance under humid service conditions.

Importantly, the bulk moisture resistance conferred by thermal modification – evidenced by a modest mass gain of only +9.3 % after 40 days at 100 % RH – is fully retained. UV irradiation is confined to the near-surface layer (≤ 80 μm), leaving the hydrophobic core of the lamella intact.

Consequently, a differentiated application strategy is proposed:

– Untreated native pine is recommended for dry service conditions (RH ≤ 65 %), where it delivers maximal strength and minimal cost;

– Two-stage modified wood (TM+UV) is optimal for humid and dynamically varying environments (RH > 75 %, cyclic wetting–drying), combining bulk moisture resistance with robust surface adhesion.

This approach ensures compliance with GOST 20850-2014 requirements (strength class C27 and above) even under prolonged exposure to humid conditions – thereby enabling the use of glued laminated beams made from thermally modified wood in critical structural applications, including swimming pools, vegetable storage facilities, industrial workshops, and covered sports complexes.

4. CONCLUSIONS

Based on a comprehensive experimental study – including determination of the modulus of rupture (MOR) in static bending of three-lamella glued beams (150 × 30 × 10 mm) – it has been established

that the two-stage treatment protocol – bulk thermal modification at 210 °C followed by surface UV irradiation at 7.4 kJ/m² – ensures maximal stability of load-bearing capacity under variable humidity conditions. This performance is critically important for long-span structural applications (spans ≥ 12–18 m).

As illustrated in Fig. 8, wet-condition beams fabricated from two-stage modified wood (TM+UV) achieve an MOR of 58.3 ± 2.1 MPa, which is only 6 % lower than that of dry control specimens (62.1 MPa); 31 % higher than wet untreated wood (44.7 MPa); 41 % higher than wet thermally modified beams without UV activation (41.3 MPa).

These results confirm that the synergistic combination of bulk thermal stabilization and selective surface photo-activation effectively mitigates the traditional trade-off between moisture resistance and adhesive bond reliability – enabling the use of engineered timber in demanding structural environments while maintaining mechanical performance close to that of native wood.

This exceptional stability arises from the dual-action mechanism of the proposed technology: firstly, bulk thermal stabilization significantly reduces hygroscopicity (mass gain of only +9.3 % after 40 days at 100 % RH), thereby suppressing cyclic swelling–shrinkage and preventing dimensional deformations and microcracking within the lamella bulk. Secondly, surface UV activation restores adhesive performance, lowering the contact angle to 58° – a result corroborated by ATR-FTIR spectroscopy, which shows increased intensities of the 3344 cm^{-1} (O–H stretching) and 1026 cm^{-1} (C–O deformation of cellulose primary alcohols) bands – confirming the re-exposure of polar functional groups and ensuring robust bonding even under aggressive service conditions.

Comparison with regulatory requirements reveals that the achieved MOR of 58.3 MPa complies with strength class C27 according to GOST 20850-2014. Moreover, this value exceeds the design bending resistance (Ru = 18 MPa) for beams spanning 12–18 m – as specified in SP 64.13330.2017 – by a factor of 3.2, providing a substantial safety margin. Additionally, the low coefficient of variation (3.6 %) confirms excellent process reproducibility and reliability for industrial-scale implementation.

Thus, we propose the use of glued laminated beams made from two-stage modified wood (TM+UV) as load-bearing elements in long-span structures operating under humid and dynamically varying climatic conditions – specifically in covered sports and retail complexes, where high occupancy and condensation pose challenges, vegetable storage facilities, swimming pools, and aquaparks, characterized by persistently high relative humidity, industrial workshops with steam emissions and cyclic moisture loading, agricultural facilities, including greenhouses and grain storage warehouses.

This technology eliminates the need for imported modified adhesives and toxic impregnation agents, while simultaneously ensuring compliance with reliability categories I–II (as per GOST 20850–2014 and SP 64.13330.2017). It thereby paves the way for scalable, serial production of eco-friendly, durable, and resource-efficient timber structures for high-reliability infrastructure – fully aligned with national strategies on import substitution and sustainable construction development in the Republic of Tatarstan and beyond.

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