Resource-saving technologies in the production of glued laminated lumber with a glue line of increased strength

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Abstract. One of the main problems of forestry is increased number of fellings and deforestation. Development of promising technologies in woodworking industry is one of the solutions to this problem. These technologies make it possible to reduce the production cost through the use of cheap and non-scarce materials and improve the quality of the resulting products to the level of premium products by improving the quality of the adhesive bond.

The aim of the study is to obtain high-quality glued timber from non-grade oak wood (Quercus Robur L.) based on urea formaldehyde (resin, subsequently treated with ultrasound and constant magnetic field. The studies have shown that strength values of the adhesive bond based on the resin, subjected to shear testing along the wood grain, are significantly higher than that of the control specimens obtained using standard technology. Also, additional studies of internal stresses in the glue line and analysis of the microstructure were carried out. They enable obtain an explanation of the strengthening effect of adhesive joint.

1. Introduction

Serious changes in gluing technologies are extremely rare today in forestry, in particular in the production of glued wood materials [1, 2]. Absence of changes takes place due to the conservatism of production and unwillingness to use innovations in their own production. It is connected with great difficulties in creating new materials and technologies [3].

At the same time, process engineers have already created a universal innovative product called glued laminated lumber. Glued laminated lumber is made of solid wood and is a set of boards glued together at an angle of 90° [4]. It can be supplied as a laminated structure depending on the requirements for glued laminated lumber [4]. Such a product has good physical and mechanical characteristics and it is used in construction as a replacement for hardwood products [5]. In particular, glued laminated lumber is often used as load-bearing structures for walls, roofs and floors in the construction of low-rise buildings. This choice of builders is due to the high rigidity and ability of...
laminated veneer lumber to withstand loads in parallel and perpendicular planes. In addition to the above-mentioned advantages, glued laminated lumber retains properties of natural wood and has its energy [4, 6].

For the first time, the production of glued laminated lumber began in Europe in the 1970s. At present, its production has become widespread throughout the world, and different wood species are used for its manufacture [7, 8]. However, despite the widespread production of laminated veneer lumber, its production in Russia remains insufficient, and the shortage of production is compensated by supplies from abroad. Therefore, it is advisable to increase the production of glued laminated lumber in Russia and improve operational characteristics to increase its competitiveness. Today, such a task is difficult to achieve for modern technologists of wood processing enterprises without the use of non-standard approaches and technological solutions. A positive effect on the performance of adhesive joints by physical fields is known [9, 10]. In this regard, it is promising to use this kind of modifying effect of a combined nature in the manufacture of glued wood materials, and, in particular, of glued laminated lumber.

Thus, according to the previous studies, it is possible to use English oak (Quercus Robur L.), to obtain glued wood materials (timber) of increased strength. The material is subjected to the combined action of ultrasound and magnetic field and obtained on the basis of the widespread urea formaldehyde (UF) resin.

2. Materials and methods

2.1. Wood origin and characteristics
Wood of English oak (Quercus Robur L.), growing in the Voronezh region, was used as the specimens to be glued. The age of the trees was 35-40 years; the moisture content of the wood specimens was 15% in equilibrium. Prepared wood specimens had the sizes of 150×20×5 mm recommended by DIN EN 205-2016 [11].

2.2. Resins
The most common and available domestic materials are adhesives based on UF resins. Therefore, the object of the study was UF resin purchased from the LLC “Infrahim Co”. (Yaroslavl, Russia). In appearance, UF resin was a homogeneous suspension from white to light yellow in color without foreign matter. Mass fraction of free formaldehyde is not more than 0.9%. The relative viscosity was 15-35 s for plywood and 35-50 s for furniture at 20±0.5°C with a 6 mm nozzle diameter. The viscometer was in the form of a reservoir. Mass fraction of non-volatile substances was 65-69%. The value of pH was 7.5-8.7. According to the manufacturer (LLC “Infrahim Co.”, Yaroslavl, Russia), UV-resin is gelatinized at 100°C for 40-65 s. The gelation time was at least 10 h at 20±1°C. A 5-10% solution of oxalic orthophosphoric acid (Infrahim, Yaroslavl, Russia) was used to gelatinize the resin at 20 ± 1 ºC. Amount of hardener (5-10 g) was per 100 g of resin (experimentally established) with the required pot life of the adhesive equal to 0.5-4.0 h.

2.3. Devices and equipment
The adhesive composition must be treated with ultrasound for 3 min to achieve the goals of modification. It must be followed by treatment with a constant magnetic field of a given intensity for 20 min.

Ultrasonic treatment was carried out on an IL 10-0.1 installation manufactured by Ultrasonic Technique (Inlabllc, St. Petersburg, Russia). The ultrasonic installation (figure 1) consisted of an ultrasonic generator and a magnetostrictor, which enabled receiving ultrasonic vibrations with a frequency of 22 kHz. Irradiation with a constant magnetic field was carried out on a magnetization installation [12]. An autotransformer was used to change the voltage. It supplied current to an electromagnet (Soyuz-Elektropribor, USSR). The electrical part of the installation made it possible to create a constant magnetic field with a strength from 0 to 30×10⁴ A/m. Magnetic field strength did
not exceed $24 \times 10^4$ A/m during operation, since the irradiated material reached the limit of magnetic saturation.

The main element of the installation for magnetic processing of specimens was an electromagnetic inductor, which consisted of two movable shoes. A current of 12 A was supplied to the winding of the electromagnet. The strength of the magnetic field was controlled by the magnitude of the supplied current and the distance between the poles of the electromagnet. The ultrasonic part of the magneto-electronic installation consisted of an ultrasonic generator, a magnetostrictive transducer and three waveguide-emitters (concentrators). The device enabled to create a constant magnetic field with an intensity of $30 \times 10^4$ A/m.

The irradiation of the adhesives of the magneto-ultrasonic installation was carried out in the following sequence. The glue under study was placed in a special fluoroplastic cuvette and treated with a magnetic field and ultrasound. The treatment was made in the mode of a given magnetic field strength, frequency of ultrasonic vibrations and time of exposure to physical fields.

![Figure 1. Schematic diagram of magnetic ultrasonic installation: 1 – electromagnet winding; 2 – electromagnet shoes; 3 – ultrasonic head; 4 – yoke; 5 – electromagnet power supply; 6 – potentiometer; 7 – generator of the ultrasonic unit.](image1)

![Figure 2. Schematic diagram of the installation for determining the internal stresses of the adhesive layer: 1 – working cell; 2, 3 – plates; 4 – adhesive layer; 5 – DC source; 6 – digital device; 7 – measuring complex.](image2)

Internal stresses determination was used as a way to control the quality of the material being created. A method was developed to implement the task of determining the internal stresses in the glue seam. An installation was created based on the so-called cantilever method, according to which the internal stresses were calculated using a specially derived analytical dependence. The method used to determine internal stresses in adhesive layers had a significant advantage over existing methods, which did not provide data on stresses over time.

A method for the continuous determination of the internal stresses arising during the curing of the adhesive layer was developed. The amount of bending of the glued plates was constantly recorded by measuring the capacitance of a flat capacitor formed by the adhesive plates with a measuring device consisted of a working cell, in which glued slabs, consisting of wooden (oak) slabs 10 cm long and 1 cm wide, were cantilevered with a thickness ratio of 1:10. Adhesive layer of a given thickness was applied between them (figure 2). The glued plates were connected to a direct current power supply and a digital analogue-to-digital converter.

The measurement of the internal stresses of the adhesive layer during the curing process was carried out according to the following scheme. An adhesive layer of a given thickness was applied
on the previously prepared surface of the plate. The second plate was laid on the first one using the gluing technology after open exposure. The residual voltages were calculated for different holding times with the help of a special program.

Working cell was calibrated at the initial stage of the work on determining the internal stresses. For this, a plate with a thickness of 0.3 mm was cut out. A layer of glue was applied to it and fixed with consoles. The sensors were used to measure the bending value of the free end of the elastic plate 2 with a step of 0.1 mm to a value exceeding the elastic bending. In this case, the value of the resulting bend was entered into the computer memory, and the capacity value was simultaneously recorded by a digital device and transmitted to the computer. Calibration results are shown in table 1.

### Table 1. Calibration of the measuring cells.

| Measurement number | Capacity, pF | Bending value, mm |
|--------------------|--------------|-------------------|
| 1                  | 16           | 0                 |
| 2                  | 15.8         | 0.05              |
| 3                  | 15.6         | 0.1               |
| 4                  | 15.4         | 0.15              |
| 5                  | 15.2         | 0.2               |
| 6                  | 15.0         | 0.25              |
| 7                  | 14.7         | 0.3               |
| 8                  | 14.4         | 0.35              |
| 9                  | 13.0         | 0.4               |
| 10                 | 12.6         | 0.45              |
| 11                 | 12.2         | 0.5               |
| 12                 | 11.6         | 0.55              |

Free end of the assembly was bent in the interlayer during glue polymerization. It was accompanied by a change in the capacity of the working cell, which simulated a flat capacitor. The change in the capacitance of the capacitor as the adhesive layer cures was recorded by a digital device and transmitted to the computer system. Internal stresses were calculated as a function of time with the help of a special program according to the formula [13]. Investigations of the microstructure of the cured adhesive layer were carried out on a scanning electron microscope JSM-6510 (Jeol, Japan).

The data obtained were processed in order to identify statistically erroneous values in the sample size. Standard STATISTICA 6.0 software package was used to process the experimental results. The reliability of the research carried out as a result of statistical calculations was 98.65%.

### 3. Results and discussion

The results obtained during the research have high practical value not only for the wood processing enterprises. These results will help to reduce deforestation through reduced area of forests under cutting. The suggested method enables to test wood specimens and subject to fracture tests to determine the ultimate shear strength along the fibers (table 2). Glued wood specimens were made according to the recommendations of DIN EN 205-2016 [11].

The increase in strength and decrease in internal stresses of the adhesive joint after treatment with ultrasound and a constant magnetic field can be explained from the point of view of the theory of intermolecular bonds described in [14]. Intermolecular bonds are bonds established between the macromolecules of the adhesive material and the active centers of the surface layer of the surfaces to be glued. This type of bonds is reversible; however, according to many researchers, they determine the processes of wetting and spreading of the adhesive over the substrate. For example, the donor-acceptor interaction between the adhesive and the surfaces is the main one. It is due to the fact that the formation of covalent bonds requires a complete overlap of the orbitals. Whereas, in reality, these processes occur only partially. Sequential exposure to ultrasound and constant magnetic field enables
to increase the number of free electrons at the interface (adhesive-glued surface), thereby increasing the wetting ability of the adhesive.

**Table 2.** Dependence of the ultimate shear strength and the magnitude of internal stresses in adhesive joints based on UF resin and oak wood on the effect of a magnetic field and ultrasound.

| Magnetic field strength, H-10^4, A/m | Frequency of ultrasonic vibrations, n, kHz | Shear strength, τ, MPa | The magnitude of internal stresses, σ, MPa |
|-------------------------------------|------------------------------------------|-----------------------|------------------------------------------|
| 0                                   | 0                                        | 5.3                   | 91.2                                    |
| 6                                   | 5                                        | 7.1                   | 82.7                                    |
| 8                                   | 5                                        | 7.6                   | 80.1                                    |
| 8                                   | 10                                       | 9.9                   | 78.4                                    |
| 24                                  | 22                                       | 11.6                  | 65.6                                    |

An increase in the breaking strength along the grain of the wood by 219% can be seen according to the data obtained as a result of the experiment. While there is a decrease in internal stresses in the glue line by 71%. The microstructure studies were performed to explain the changes in the polymer under the action of physical fields. Photographs of the microstructure of the studied polymer adhesives are shown in figure 3.

![Microphotographs](image)

**Figure 3.** Microphotographs (×45000) of initial glue (a) and glue processed in a magneto-ultrasonic field (b).

Structure densification and reduction in the intermolecular space are clearly observed, comparing the structure of an adhesive specimen subjected to sequential treatment with ultrasound and constant magnetic field (figure 3b) with an untreated one (figure 3a). The obtained research results confirm the assumptions put forward on the basis of the theory of intermolecular bonds and explain the densification of the structure due to an increase in the activation energy of molecules. Change in the structure of the polymer of the KF resin under the action of sequential treatment with ultrasound and constant magnetic field is the most logical and correct explanation for the decrease in internal stresses in the glue line and increase in the strength characteristics of the glue joint.

Statistical processing of the experimental results was carried out on a computer. The following statistical characteristics were determined during the primary processing of experimental data, specimen size and random observations X₁, X₂, …, Xₙ: sampling mean  \( \bar{X} \), sampling variance \( S^2 \), standard deviation \( S \), coefficient of variation \( V \), and error of the mean \( S(x) \).

4. **Conclusion**
As a result of the obtained experimental data show significant changes in the physical and mechanical properties of glued oak wood specimens obtained on the basis of KF resin and subjected to sequential
treatment with ultrasound and a constant magnetic field. The ultimate shear strength was increased by 219%, and the value of internal stresses arising during curing in the glue joint was reduced by 71%. Also, structure dispersion was proved by the analysis of the obtained images of the microstructure of the adhesive seam. In conclusion, it can be noted that the use of non-varietal oak wood (*Quercus Robur* L.) and KF resin as a binder is advisable for obtaining glued wood materials (timber) and its quality significantly increases without major changes in the technology of its production. The proposed technology will reduce the number of fellings and increase the use of wood for production of glued wood materials (timber) with increased strength characteristics.

Acknowledgments
The work was carried out with the financial support of the Russian Fund for Basic Research (project 20-08-00165).

References
[1] Jeleč M, Varevac D and Rajčić V 2018 Cross-laminated timber (CLT) – A state of the art report. *Journal of the Croatian Association of Civil Engineers* 70(2) 75 DOI: 10.14256/JCE.2071.2017.
[2] Lou Z, Yuan T, Wang Q, Wu X, Hu S, Hao X, Liu X and Li Y 2021 Fabrication of crack-free flattened bamboo and its macro-/micro-morphological and mechanical properties. *J. Renew. Mater.* 9(5)959DOI: 10.32604/jrm.2021.014285
[3] Dolan J D, Wilson A, Brandt K, Bender D A and Wolcott M P 2019 Structural design process for estimating cross-laminated timber use factors for buildings. *BioResources* 14(3) 7247 DOI: 10.15376/biores.14.3.7247-7265
[4] Espinoza O and Buehlmann U 2018 Cross-laminated timber in the USA: Opportunity for hardwoods? *Current Forestry Reports* 4(1) I DOI 10.1007/s40725-018-0071-x
[5] Hindman D P and Bouldin J C 2015 Mechanical properties of southern pine cross-laminated timber. *J. Mater. Civil.Eng.* 27(9) 4014251 DOI 10.1061/(ASCE)MT.1943-5533.0001203
[6] Espinoza O, Trujillo V R, Laguarda Mallo M F and Buehlmann U 2016 Cross-laminated timber: Status and research needs in Europe. *BioResources* 11(1) 281 DOI: 10.15376/biores.11.1.281-295
[7] Li X, Ashraf M, Subhani M, Ghabraie K, Li H and Kremer P 2021 Withdrawal resistance of self-tapping screws inserted on the narrow face of cross laminated timber made from Radiata Pine. *Structures* 31(2) 1130 DOI 10.1016/j.istruc.2021.02.042
[8] Li X, Ashraf M, Subhani M, Kremer P, Li H and Anwar-Us-Saadat M 2021 Rolling shear properties of cross-laminated timber (CLT) made from Australian radiata pine – An experimental study. *Structures* 33(3) 423 DOI 10.1016/j.istruc.2021.04.067
[9] Nikulin S S, Shul'Gina Y E, Poyarkova T N, Popov V M, Latynin A V and Nikulina N S 2014 Specific features of rubber recovery from a latex with N,N-Dimethyl-N,N-Diallylammonium chloride and the action of magnetic field. *Russ. J. Appl. Chem.* 87(7) 972 [in Russian]
[10] Popov V M, Latynin A V, Shendrikov M A and Nikulin S S 2013 Mechanism by which electric field affects the strength of glue joints. *Russ. J. Appl. Chem.* 86(4) 599 [in Russian]
[11] DIN EN 205-2016 *Adhesives - Wood Adhesives for Non-structural Applications - Determination of Tensile Shear Strength of Lap Joints* 2016 (Berlin: German Institute for Standardization)
[12] Popov V M, Ivanov A V, Murzin V S, Novikov A P, Shendrikov M A and Latynin A V, RU Patent No. 2328788 (10 July 2008)
[13] Popov V M, Ivanov A V, Novikov A P, Shendrikov M A and Latynin A V 2012 RU Patent No. 2456586 (20 July 2012)
[14] Villenave J J 2005 *Assemblage par Collage* (Malakoff: Dunod) p 319