TiAM kwartalnik naukowo-techniczny
TECHNOLOGIA I AUTOMATYZACJA MONTAŻU
ZESPOŁÓW • MASZYN • URZĄDZEŃ

Jacek Ogrodniczek[1], Anna Rudawska[2],
Izabela Miturska-Barańska[3], Elżbieta Doluk[4]

DOI: 10.7862/tiam.2022.2.1

INFLUENCE OF TECHNOLOGICAL FACTORS ON THE STRENGTH OF WOOD ADHESIVE JOINTS

WPŁYW CZYNNIKÓW TECHNOLOGICZNYCH NA WYTRZYMAŁOŚĆ DREWNIANYCH POŁĄCZEŃ KLEJOWYCH

Abstract

The article presents the results of a statistical analysis of adhesive joints with identical structural and material factors in relation to technological factors. Four types of adhesive joints were made: butt joints, lap joints, scarf joints and wedge joints. The joined materials were pine and oak wood. Each type of adhesive joint was joined in the following wood configurations: pine-pine, pine-oak, oak-oak. The technological factors were the type of adhesive, the humidity of the wood and the surface preparation of the samples. The U Mann-Whitney test was used to perform the statistical analysis. Results of statistical tests showed the influence of the used adhesive on pine-oak butt joints and wood moisture on pine-oak butt joints. Furthermore, the effect of wood configurations on the strength for each of the tested adhesive joints was compared using the Dunn's statistical test. The test showed that there were not statistical differences between the joints in configurations pine-pine and pine-oak.

Keywords: adhesive joints, statistical analysis, wood adhesives

Streszczenie

W artykule przedstawiono wyniki analizy statystycznej połączeń klejowych o jednakowych czynnikach konstrukcyjnych i materiałowych względem czynników technologicznych. Wykonano 4 rodzaje konstrukcji połączeń klejowych: doczołowe, zakładkowe, skośne, klinowe. Materiałami łączonymi było drewno sosny i dębu. Każdy rodzaj połączenia klejowego łączono w konfiguracji drewna: sosna-sosna, sosna-dąb, dąb-dąb. Czynnikami technologicznymi był rodzaj kleju, wilgotność drewna oraz przygotowanie powierzchni próbek. Do wykonania testu statystycznego wykorzystano test U Manna-Whitneya. Analiza statystyczna wykazała wpływ rodzaju kleju na połączenia doczołowe sosna-dąb oraz wilgotności drewna na połączenia skośne sosna-dąb. Ponadto porównano wpływ gatunku drewna na wytrzymałość każdego z badanych połączeń klejowych przy pomocy testu Dunna. Test wykazał, że połączenia sosna-sosna nie różnią się statystycznie od połączeń sosna-dąb.

Słowa kluczowe: połączenia klejowe, analiza danych, kleje do drewna

1. Introduction

Wood is a natural construction material widely used in the civil engineering and furniture industry. It is anisotropic material with porous structure. The mechanical properties of wood depend on the type and species of timber used. Wood can be divided into two types of trees: coniferous (e.g. pine, spruce) and deciduous (e.g. oak, alder) [1,2,3].

Wood is susceptible to ageing and loss of strength. The main factors affecting the strength of wood are temperature, changes in humidity, water, insects and fungi. There are a lot of methods which modify the structure of the wood and prepare this material for required application. This method can be divided into 4 categories: heat treatment, chemical treatment, surface treatment and impregnation [4,5,6].

[1] MSC. Eng. Jacek Ogrodniczek (corresponding author), Politechnika Lubelska, Wydział Mechaniczny, Katedra Informatyzacji i Robotyzacji Produkcji, ul. Nadbystrzycka 36, 20-618 Lublin, e-mail: jacek.ogrodniczek@pollub.edu.pl, ORCID: 0000-0002-6484-2245.

[2] Prof., Ph.D., D.Sc., Eng. Anna Rudawska, Politechnika Lubelska, Wydział Mechaniczny, Katedra Informatyzacji i Robotyzacji Produkcji, ul. Nadbystrzycka 36, 20-618 Lublin, e-mail: a.rudawska@pollub.pl, ORCID: 0000-0003-3592-8047.

[3] PhD. Eng. Izabela Miturska-Barańska, Politechnika Lubelska, Wydział Mechaniczny, Katedra Informatyzacji i Robotyzacji Produkcji, ul. Nadbystrzycka 36, 20-618 Lublin, e-mail: i.miturska@pollub.pl, ORCID: 0000-0003-4140-4768.

[4] PhD. Eng. Elżbieta Doluk, Politechnika Lubelska, Wydział Mechaniczny, Katedra Informatyzacji i Robotyzacji Produkcji, ul. Nadbystrzycka 36, 20-618 Lublin, e-mail: e.doluk@pollub.pl, ORCID: 0000-0003-2605-1394.

Heat treatment enhances wood structure by reducing the fluid content in the material and increases dimensional stability. However, it has a negative effect on static and dynamic strength. The chemical treatment of wood modifies the wood cell walls and increases the strength of the material. That method protects wood against moisture [7,8].

The most common method of modifying wood is surface treatment and impregnation. The surface of the wood is abraded with a sanding tool to prepare the surface for application of a layer impregnating agent, which protects the material from external factors. Impregnating agents are usually of natural origin and are based on linseed oil [9,10,11].

Wood selected for the study was pine (*Pinus sylvestris*) and oak (*Quercus robur*). Pine wood is a commonly used material, which is due to its easy availability. Pine trees can adapt to different environmental conditions and grow fast. Oak wood has high strength and is resistant to external factors such as insects and fungi [12].

The aim of this paper was to compare the influence of material and technological factors on adhesive joints with different type of joint construction. The technological factors in the study were type of the used adhesive, preparation of surface and wood moisture. Statistical analysis comparing adhesive joints was prepared using RStudio and Statistica software.

2. Research methodology

During the process of preparation adhesive joints, samples were divided according to the type of wood, joints construction and technological factors such as the type of adhesive, wood moisture and the surface treatment of the wood. In the study, one sample of each adhesive joint was made, characterized by selected construction, material and technological factors.

2.1. Samples preparation

96 samples were prepared for each wood species. Half of them had 6-8% wood humidity (dry) whereas the other half had 16-18% wood humidity (wet). The length of the sample was 50 mm and cross-section was 20 x 20 mm. The first step of the study was a mechanical treatment which shaped samples for the selected adhesive joints construction. In the study, the following adhesive joints were made: butt joints, lap joints, scarf joints and wedge joints. The dimensions of the samples used in the aforementioned adhesive joints are shown in fig. 1-4.

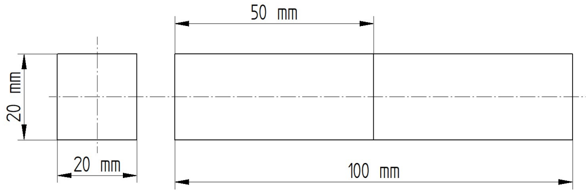

Fig. 1. Dimension of sample used in butt joint

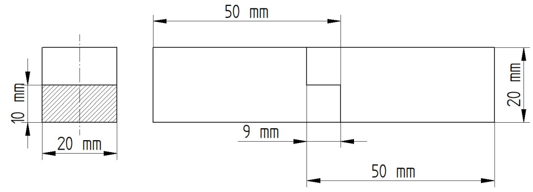

Fig. 2. Dimension of sample used in lap joint

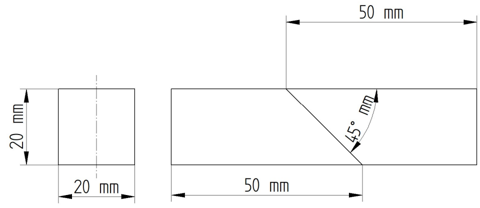

Fig. 3. Dimension of sample used in scarf joint

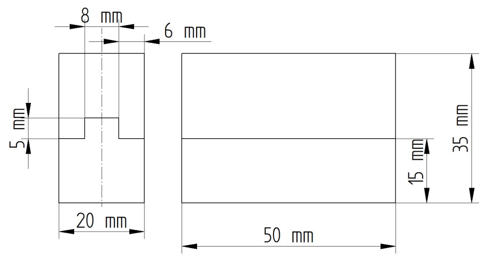

Fig. 4. Dimension of samples used in wedge joint

For each construction of the adhesive joint, a division was made into the type of used wood and humidity. Materials were joined in the following configurations: pine-pine, pine-oak, oak-oak. As a result of the division, 8 adhesive joints of identical construction and material were formed. In the case of adhesive joints with the wedge construction, where dissimilar materials were used, the grove was formed from the oak wood. In addition, to increase the number of possible factors influencing the adhesive joints, the samples were further processed. The surface of half the dry and wet samples was abraded with P120 sandpaper. The abrasion of the adhesive samples was done manually by 20 making 20 circular movements.

During the sample preparation process, the ambient temperature was 23°C ± 1°C and humidity was 50% ± 1%.

2.2. Adhesive technology and tensile tests

Polyurethane adhesive (trademark: PUR adhesive, producer: Würth, Künzelsau, Germany) and PVAC-based adhesive (trademark: D3 PVA wood adhesive, producer: Würth, Künzelsau, Germany) were used to make adhesive joints. This made it possible to create adhesive joints with identical constructional and material factors, as well as identical technological processing, differing in the adhesive used. Both adhesives were one-component.

While making adhesive joints, the adhesive was applied to the surface of one sample of the adhesive joint. The bottle of polyurethane adhesive had a dispenser to apply the adhesive. In the case of the PVAC-based adhesive, the adhesive was applied with a spatula.

The adhesive joints were subjected to curing for a period of 7 days. The samples were pressed by a specimen holder, which made an impact with a value of 0.8 MPa. Strength tests of adhesive joints were carried out on a Zwick/Roell Z150 testing machine according to PN-EN 311:2004 [13].

2.3. Statistical analysis

The aim of the statistical analysis was to demonstrate the influence of technological factors on the strength of adhesive joints with equal structural and material factors. Due to the lack of normal distribution in most of the compared groups, the non-parametric statistical U Mann Whitney test was used to perform the statistical analysis. The test is equivalent to the parametric t-student test. As hypothesis H_0, the similarity between the strength of adhesive joints in the groups studied was accepted [14,15].

The results of the strength tests were compared with respect to one of the following technological factors: the type of adhesive used, the method of preparation of the surface of the samples and wood humidity. During the comparative analysis, against one factor, the remaining technological factors in the group were treated as the same type of adhesive joint. The test significance value for the U Mann-Whitney test was $\alpha = 0{,}05$.

The statistical analysis also compared the structural strength of the adhesive joints against the material factor. Dunn's test was used to make the comparison. Technological factors were not considered when comparing the strength of the joint structure.

3. Results

3.1. Tensile strength results

The results of the tensile strength of the tested adhesive joints are shown in table 1. The table presents the descriptive statistics for the adhesive joints in relation the joint construction and material factor.

Table 1. Tensile strength results of the tested adhesive joints

Joint	Wood	Number of samples	Mean [MPa]	Median [MPa]	Maximum [MPa]	Minimum [MPa]	Variance [MPa]	Stand. Deviation [MPa]
Butt joint	Oak-Oak	8	2.783	2.209	1.539	5.276	1.870	1.368
	Pine-Oak	8	1.710	1.829	0.889	2.704	0.533	0.730
	Pine-Pine	8	1.456	1.465	0.616	2.662	0.423	0.650
Lap joint	Oak-Oak	8	3.534	3.171	2.205	5.372	1.427	1.194
	Pine-Oak	8	2.194	2.264	1.309	3.499	0.647	0.804
	Pine-Pine	8	2.132	2.231	0.832	3.330	0.631	0.794
Scarf joint	Oak-Oak	8	1.149	1.056	0.720	1.718	0.129	0.359
	Pine-Oak	8	0.646	0.633	0.359	0.929	0.031	0.177
	Pine-Pine	8	0.585	0.565	0.389	0.774	0.015	0.121
Wedge joint	Oak-Oak	8	3.382	3.373	1.996	4.810	0.826	0.909
	Pine-Oak	8	1.812	1.840	1.397	2.184	0.077	0.278
	Pine-Pine	8	1.948	1.712	1.433	3.430	0.429	0.655

On the basis of the results from the table 1 it can be concluded that the adhesive joints with the scarf joint construction obtained the lowest strength of all the adhesive joint constructions. The highest strength was achieved by three adhesive joints:

- Butt joint/Oak-Oak/Wet/PUR/Unpolished (5.276 MPa),
- Lap joint/Oak-Oak/Wet/PUR/Polished MPa (5.277 MPa),
- Lap joint/Oak-Oak/Wet/PVAC/Unpolished (5,372 MPa).

3.2. Statistical analysis results

The performed statistical results of the U Mann-Whitney test for each type of adhesive joint construction are presented in table 2-5. The tables show the p-value for each type of joint compared against one technological factor.

Table 6 reveals the results of Dunn's tests which compared the strength of adhesive joints for each kind of material used.

Table 2. Results of U Mann-Whitney tests for butt joints

Butt joints	Type of material		
	pine - pine	pine - oak	oak - oak
	p-value		
Type of adhesive	0.886	0.486	0.486
Wood humidity	0.486	0.029	0.686
Surface preparation	0.686	0.343	0.886

Table 3. Results of U Mann-Whitney tests for lap joints

Lap joints	Type of material		
	pine - pine	pine - oak	oak - oak
	p-value		
Type of adhesive	0.343	0.400	0.343
Wood humidity	0.200	0.857	0.486
Surface preparation	0.686	0.229	0.486

Table 4. Results of U Mann-Whitney tests for scarf joints

Scarf joints	Type of material		
	pine - pine	pine - oak	oak - oak
	p-value		
Type of adhesive	0.343	0.029	0.200
Wood humidity	0.886	0.886	0.486
Surface preparation	1.000	0.686	0.886

Table 5. Results of U Mann-Whitney tests for wedge joints

Wedge joints	Type of material		
	pine - pine	pine - oak	oak - oak
	p-value		
Type of adhesive	0.686	0.486	0.343
Wood humidity	0.114	0.686	0.686
Surface preparation	0.686	0.114	0.686

Tabela 6. Dunn's test results

Compared values between materials	Type of joint			
	Butt joint	Lap joint	Scarf joint	Wedge joint
	p-value			
Oak - oak, Pine - oak	0.472	0.069	0.019	0.009
Oak - oak, Pine - pine	0.065	0.049	0.003	0.013
Pine - pine, Pine - oak	1.000	1.000	1.000	1.000

Analysing the results of statistical calculations comparing technological factors for individual adhesive joint constructions, statistical significance can be seen in 2 cases. Both of them concern joints formed from pine-oak materials.

More information about the results of statistical tests is presented in the next point.

4. Discussion of results

The first type of joints showing statistical significance are butt joints. The technological factors which indicates the difference in the strength of adhesive joints is the moisture content in the wood. The joined pine and oak samples showed equal moisture content. In this test, adhesive joints were compared between a group of adhesive whose wood moisture content was 6-8% and a group whose wood moisture was 16-18%. The p-value for the U Mann--Whitney test comparing effect of wood moisture of butt adhesive joints formed by joining pine and oak samples was $p = 0.029$. This value is lower than the test significance value.

The second type of joints showing statistical significance are scarf joints. The technological factor which affects the difference between the compared strength results of adhesive joints is the type of adhesive used for joining pine and oak samples. The p-value for U Mann-Whitney test comparing the effect of glue on the strength of butt joints formed by joining pine and oak samples is 0.029. The value is lower than the test significance value.

The remaining results of statistical calculations performed with the Mann-Whitney U test, show that there is no statistical significance for the tested adhesive joints compared against technological factors.

The strength results were also compared against the material factor for each type of joint design. Dunn's test was used to perform statistical calculations comparing adhesive joints against the material factor (Table 6). The graph in Fig. 5 illustrates the median and standard deviation of the strength values of adhesive joints of different designs against the material used in the adhesive joints.

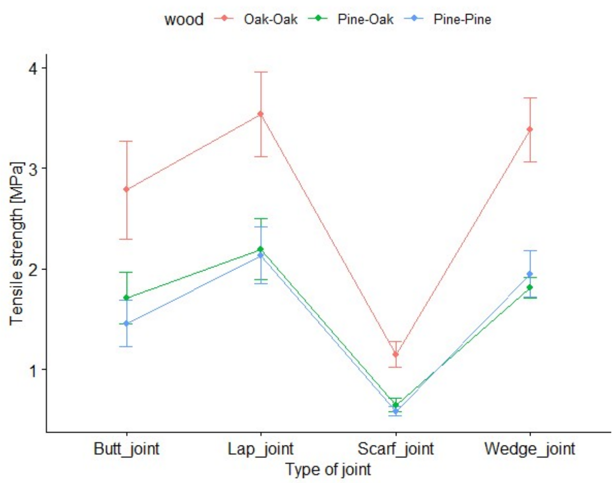

Fig. 5. Strength of adhesive joints

From the graph in Fig. 5, it can be concluded that for all adhesive joint designs, the strength of pine wood joints and pine and oak wood joints are similar. This fact is confirmed by the Dunn test.

The butt joint shows a lack of statistical significance, resulting from the Dunn statistical test result. In the case of this adhesive joint construction, there are no statistical differences between the material factors. The lack of statistical significance is manifested by the comparison of the results of the strength of lap joints between adhesive joints of oak-oak and pine-oak samples.

5. Conclusion

The performed strength tests and statistical analysis allow the following conclusions to be drawn:

- the technological factor significantly affecting the strength of a butt adhesive joint is the moisture content of the wood,
- a technological factor significantly affecting the strength of a slanting adhesive joint is the type of glue used,
- technological factors such as the type of adhesive used, the moisture content of the wood, or the preparation of the surface of the glued specimens do not affect the strength of lap and wedge adhesive joints of wood,
- in adhesive joints formed as a result of joining pine wood and oak wood, oak wood does not influence the increase of the strength of the adhesive joint.

Bibliography

1. Ramage Michael, Henry Burridge, Marta Busse-Wicher, George Fereday, Thomas Reynolds, Darshil U. Shah, Gaunglu Wu, 2017. “The wood from the trees: The use of timber in construction”. *Renewable and Sustainable Energy Reviews, 68* (Part 1), 333-359.
2. Ülker Onur, 2016.Wood Adhesives and Bonding Theory. In *Adhesives – Applications and Properties*, 271-288. InTech.
3. Stoeckel Frank, Johannes Konnerth, Wolfgang Gindl--Altmutter, 2013.”Mechanical properties of adhesives for bonding wood – A review”. *International Journal of Adhesion and Adhesives*, vol. 45: 32-41.
4. Sonderegger Walter, Katalin Kránitz, Claus-Thomas Blues, Peter Niemz, 2015. “Aging effects on physical and mechanical properties of spruce, fir and oak wood”. *Journal of Cultural Heritage*, vol. 16(6): 883-889.
5. Konnerth Johaness, Wolfgang Gindl, 2008. “Observation of the influence of temperature on the mechanical properties of wood adhesives by nanoindentation”. *Holzforschung*, vol. 62: 714-717.
6. Cruz Helena, Jose Saporiti Machado, 2013. ”Effects of beetle attack on the bending and compression strength properties of pine wood”. *Advanced Materials Research*, vol. 778: 145-151.
7. Sikora Adam, Frantisek Kačík, Milan Gaff, Veronika Vondrová, Tatiana Bubeníková, Ivan Kubovský. 2018. “Impact of thermal modification on color and chemical changes of spruce and oak wood”. *Journal of wood Science* 64: 406-416.
8. Kubovský Ivan, Danica Kačíková, Frantisek Kačík, 2020. “Structural Changes of Oak Wood Main Components Caused by Thermal Modification”. *Polymers* 12(2), 485.
9. Addis Clark, Koh Rachel, Gordon Melissa, 2020. “Preparation and characterization of a bio-based polymeric wood adhesive derived from linseed oil”. *International Journal of Adhesion and Adhesives*, vol. 102.
10. Peng Yao, Wang Yujio, Chen Pingan, Wang wen, Cao Jinzhen, 2020. “Enhancing weathering resistance of wood by using bark extractives as natural photostabilizers in polyurethane-acrylate coating”. *Progress in Organic Coatings*, vol. 145.
11. Arminger Benjamin, Julien Jaxel, Markus Bacher, Wolfgang Gindl-Altmutter, Christian Hansmann, 2020. “On the drying behavior of natural oils used for solid wood finishing”. *Progress in Organic Coatings*, vol. 148.
12. Acosta Andrey Pereira, Jalel Labidi, Henrique Römer Schulz, Ezequiel Gallio, Kelvin Techera Barbosa, Rafael Beltreme, Rafael de Avila Delucis, Darci Alberto Gatto, 2020. “Thermochemical and Mechanical Properties of Pine Wood Treated by In Situ Polymerization of Methyl Metharylate (MMA)”. *Forests* 11(7), 768.
13. PN-EN 311:2004 – Płyty drewnopochodne – Wytrzymałość na odrywanie warstwy przypowierzchniowej – Metoda badania.
14. Rabiej Małgorzata, 2018. “Analizy statystyczne z programami Statistica i Excel”. Gliwice: Wydawnictwo Helion.
15. Stanisz Stanisław, 2006. “Przystępny kurs statystyki z zastosowaniem STATISTICA PL na przykładach z medycyny – Tom 2. Statystyki podstawowe”. Kraków: StatSoft Polska.