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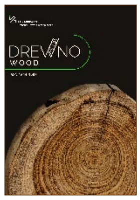

The Influence of Moisture Content on Strength of Window Corner Joint

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The tendency to improve the energy efficiency of windows has led to an increase in the number of panes used. The greater weight of the window sash leads to a loss of its geometry during normal usage. This deformation of geometry is caused by its own weight, and thus reduces the efficiency of preventing heat loss. All the positive effects that are obtained by using multiple panes of glass are thus lost.

As window manufacturers often try to cut production costs by shortening the time of kiln drying, this paper researches the effect of using elements with different moisture content.
Articles on similar topics were reviewed and it was found that there were no available data on the researched topic. Only about 20 different articles on similar topics were found, but the starting conditions or input was greatly different. Also, there are no official standards that cover the strength of window corner joints. This paper analyzes the influence of the change in moisture of the elements on the strength of the joint. Three groups of window corner joint samples were examined. The first group of samples was the control group that was supposed to determine the strength of the joint when the window beams were made with the recommended moisture according to a corresponding standard (12 ± 2%). In the second and third groups, the moisture of the beams was taken as a variable factor, namely the moisture content of 18 ± 2%.

The results of this study show that the strength values of the currently used corner joints (double mortise and tenon) are different at different moisture contents. As expected, the samples with the recommended moisture content had higher strength values than the samples with the higher moisture content.

There are many challenges in proper kiln drying and the final moisture content has a crucial impact on window strength. As windows have a specific purpose in buildings, they should have sufficient strength to be properly used over a long period. These obtained results should demonstrate the importance of the moisture content of wooden beams used in window production.

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Introduction

The construction of windows has undergone great changes in the last 30 years. Single-glazed windows have been replaced by double-glazed and triple-glazed windows, which reduce heat losses. The usage of a larger number of glass panes of a greater thickness (thicker than 4 mm) has required the production of window elements that have a larger cross section than was the case with previous construction solutions. Currently, the most common beams used in window production have a cross section of 68 x 80 mm. The increase in the number of glass panes, and the dimensions of the beams has led to growth in the weight of the window sash. This change has called into question the durability of the window itself and how much it can respond to the conditions of usage. The question also arises as to how much a window can meet the conditions of energy loss if it loses its dimensional stability. For example, in one hour at a wind strength of 8 m/s and different external and internal temperatures on the composition of a double window, 3 m^3 of air passes through a 1 m long joint, and on the composition of a box window up to 8 m^3 of air passes through a 1 m long joint [Vasiljević and Banjac 2010] . If the air flow of a "well-made" window is analyzed, we can only assume how many times the heat losses would increase if the dimensional stability of the window sash was lost during usage due to the impossibility of the specified corner joint to perform its function. According to [Niklewski and Fredriksson 2019], moisture has a significant impact on surfaces that are directly exposed to moisture (and rain). As windows are under the influence of outside weather conditions for the good part of the year, high levels of moisture and rain are normal occurrences. According to [Bomba et al. 2014], the effect of high levels of moisture and water may lower the bonding strength by about five times.

A review of the literature and scientific papers from relevant sources[1] was performed using key words related to this topic. The scope of the analysis included all papers that were available in an electronic version. According to the changes in the terms of the number and thickness of glass, a larger number of papers on this topic was expected. Within the papers where this topic was dealt with (not necessarily the corner joints of windows, but joints in general), there is no systematic data input, which further complicates defining the starting point for further work.

The analysis of papers was performed based on factors that affect the strength of the joint [Skakić and Krdžović 2002]: machining accuracy, closeness of fit, type of wood, moisture of the wood, gluing regimes, type of joint and gluing surface.

Most of the authors based their research on pine (*Pinus nigra*) as the dominant type of wood used in the construction of windows [Altınok et al. 2010; Podlena et al. 2017; Altinok et al. 2013], while others used beech (*Fagus sylvatica*) [Hu and Guan 2019; Derikvand, Ebrahimi, and Eckelman 2014]. A window represents a barrier between the external and internal environment with very large climatic oscillations during the year (temperature and humidity); therefore, the stresses in the joint caused by them probably have a great influence on the strength and durability of the joint. Hence, it is very important for the samples to be dried and conditioned to the right moisture content, at around 12±2% [Elek et al. 2020; Hu and Guan 2019; Podlena, Borůvka, and Bomba 2015; Prekrat et al. 2014]. A review of the standards and scientific papers in the field of wooden windows leads to the conclusion that it is completely unknown how effective the currently used joint is. The only thing we can say with certainty is that a corner joint formed with a mortise and tenon is widely used in practice. The results from these tests should provide a starting point in research on the strength of window corner joints. Also, tests should suggest a possible change in the type of joint used in window manufacturing.

The aim of the paper is to determine the effect of the moisture content on the average corner joint strength of a window made from pine timber with a IV68 profile. An additional aim is to determine if there is any effect on the corner joint if the horizontal and vertical beams have different moisture contents. This is a common occurrence during manufacturing when storing window elements, and it is useful to know if those elements with a higher moisture content lower the overall quality of the product.

Materials and methods

Since windows have a specific place in the building (they are located in a place that has the strictest operating conditions – on the inside there is a relatively constant climate, while on the outside the climate is quite variable with oscillations in weather conditions), the corner joint is influenced by multiple factors. With changes in these factors, the quality of the joint also changes, thus it is very important to know and understand their influence. The factors that affect the quality, i.e. the load-bearing capacity of the window corner joint, are the type of joint, gluing surface, machining accuracy, closeness of fit, type of wood, wood moisture and gluing regimes. In Figure 1 a flowchart of the research methodology is given.

[1] List of researched electronic journals is given in chapter 6.

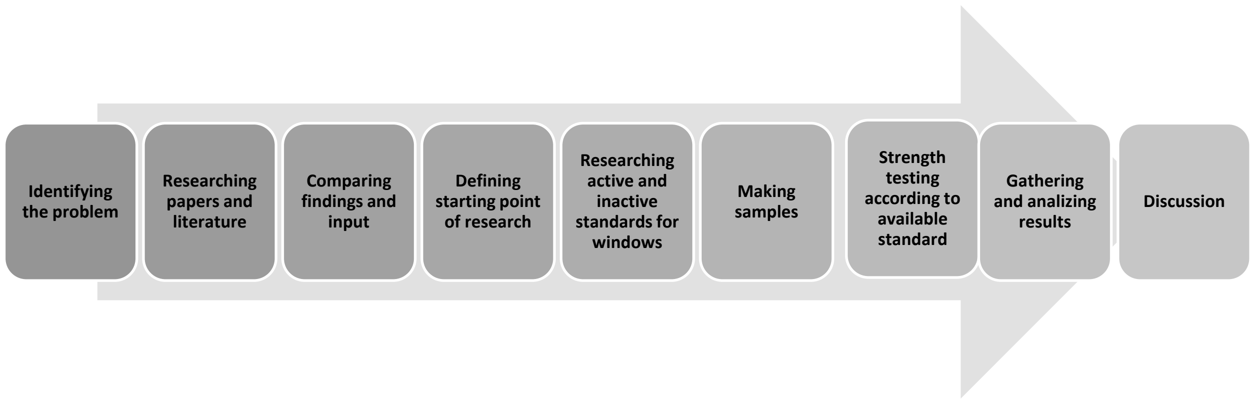

Fig. 1. Flow chart of research methodology

Given the lack and inconsistency of basic information about corner joints in windows, the initial factor for investigating the strength of the joint, which is taken as a variable in this paper, is the moisture content of the wood. The variation in this factor finds its foundation in the everyday practice of domestic producers. Often during the dehumidification kiln drying process, manufacturers decide to dry the material to a higher moisture content than recommended in order to reduce drying costs. For this reason, a test was conducted in parallel on three groups of corner joints with different moisture contents:

1. A joint when both the horizontal and vertical beams are dried to a moisture content of 12 ± 2%
2. A joint when the horizontal beam is dried to a moisture content of 12 ± 2% and the vertical to a moisture content of 18 ± 2%
3. A joint when the vertical beam is dried to a moisture content of 12 ± 2% and the horizontal to a moisture content of 18 ± 2%.

The other listed factors were kept constant for the purposes of the research. The used joint is a double tenon and mortise, and the samples are made of sawn pine (Pinus nigra), as it is one of the three commonly used types of wood for making windows (in addition to oak (Quercus robur) and spruce (Picea abies). This study should highlight the qualities and shortcomings of the mentioned joint, i.e. to give maximum values of the durability of the joint and as such represents the starting point for further research on this issue.

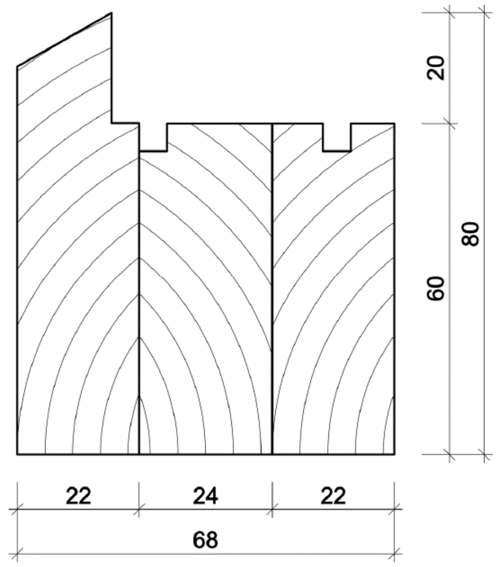

Fig. 1. Transverse appearance and dimensions of window frame beam (given dimensions are in mm)

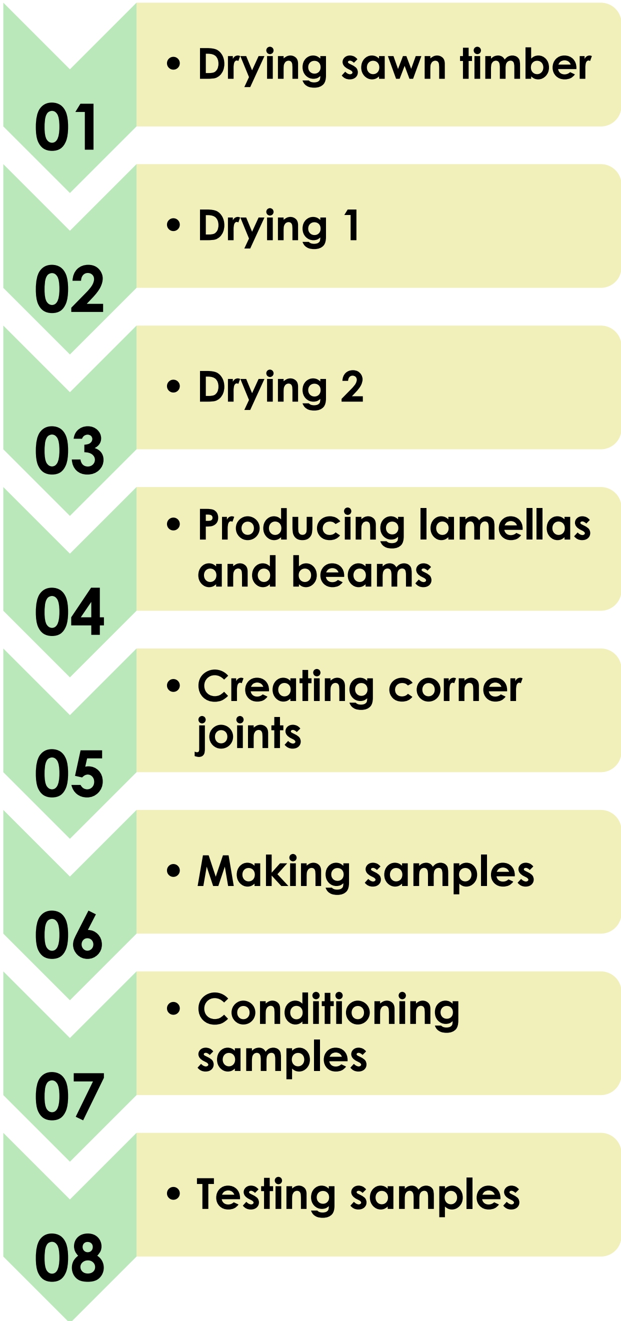

Fig. 2. Flow chart of research process

Similar information that could act as the starting point for further work could not be found in any of the papers listed. The samples were made in a company that produces wooden doors and windows. The cross section of the beams used for making the samples was 68 x 80 mm (Figure 2), while the beams themselves ware made of three lamellas. The dimensions of the outer lamellae are 22 x 80 mm and the middle 24 x 80 mm. A window with the specified cross section (IV68) is the most common window profile produced in local companies. All the samples had the same type of joint, a double mortise and tenon with a constant gluing surface of around 0.225 m^2.

PVAc class D3 glue was used to join the lamellas and corner joints of the window samples. During the production process, the machining accuracy and the closeness of fit were controlled. Figure 3 shows the flow chart of the research process.

After the period of natural drying, the material was sorted by thickness (for the middle and outer lamellas) and sent for dehumidification kiln drying. The first group of sawn timber came out of the kiln after reaching an equilibrium moisture content of 18 ± 2%. The rest of the sawn timber left the dehumidification kiln after the moisture content reached 12 ± 2%. The dried sawn timber was then cut into elements with the appropriate excess. After production of the lamellas, their moisture was checked. After checking the moisture, the lamellas were glued according to the pattern shown in Figure 2. The glue was applied by hand.

The profiles and joints were made at SCM's machining center. Before joining, the thicknesses of the mortise and tenon were measured to determine the machining accuracy and the closeness of fit. The measurement was performed with a caliper with an accuracy of 0.01 mm, at two measuring points, as shown in Figure 4.

After measuring, the beams were classified according to their moisture content into three groups and the frames were joined in accordance with the plan of the experiment, Table 1.

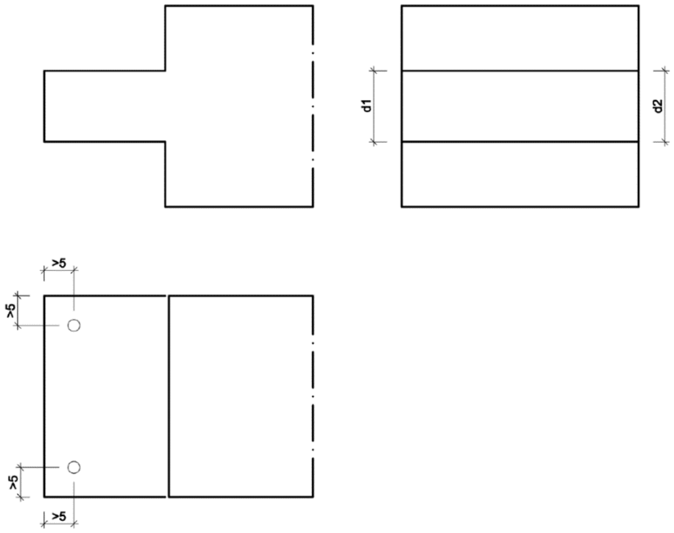

Fig. 3. Measuring points

Table 1. Division of samples into groups

Group number	Number of samples	Moisture (%)		Coefficients of variation
		Vertical beams	Horizontal beams	
1	20	12±2	12±2	0.1767
2	16	18±2	12±2	0.2162
3	20	12±2	18±2	0.1459

The obtained samples were conditioned at a temperature of 20 ± 2 °C and air humidity of 50 ± 5% for a period of 15 days. The moisture of the elements was checked on 5 randomly selected samples from each group.

Due to the lack of a standard intended for testing the strength of corner joints of wooden windows, the test was performed according to the standard for testing PVC joints – EN 514, Figure 5. A similar testing method was used by other authors [Podlena et al. 2017; Podlena, Borůvka, and Bomba 2015]. In this particular case, it was thought that a standardized test was a better choice.

According to standard EN 514:2018, the samples were made as window corners so that one segment should have a length of 385 ± 2 mm, and the diagonal distance from the ends of both segments is 400 ± 2 mm. The sample was positioned on 2 trolleys in order to eliminate side forces, as shown in Figure 5. Force was applied as axial load on the edge of the sample with the speed of application of 50 mm/min. Force was applied until the sample failed.

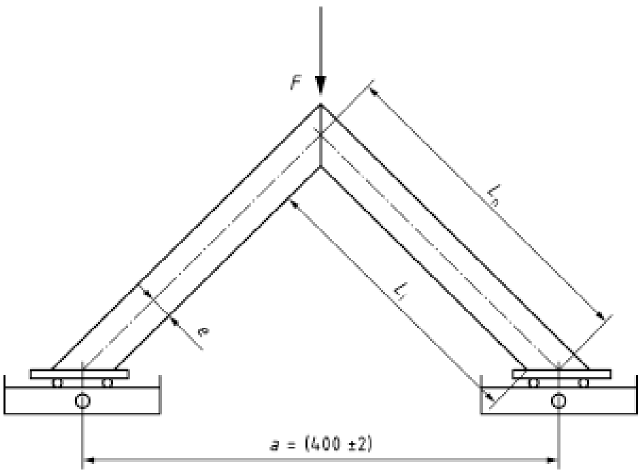

Fig. 5. Direction of force during test according to standard EN 514:2018

Results and discussion

Guided by the order of operations during production, as well as the order of data collection, Table 2 gives the results related to the machining accuracy.

In Table 2, column 6, the measured values of the mortise and tenon thickness after the moisture of the beams was changed from 18 ± 2% to 12 ± 2% are given. From these data it can be seen that, with the beams having the lower moisture content, the connection would be made with a larger gap in relation to the beams of the higher moisture content. The newly formed gap would be -0.54 mm for Group 2 (an increase in the gap by 0.1895 mm) and -0.5506 mm for Group 3 (an increase in the gap by 0.1966 mm). In this case, both groups of samples have a clearance value that greatly exceeds the recommended maximum clearance value, and thus contribute to weakening of the corner joint [Potrebić 1994].The optimal gap for a mortise and tenon joint is 0.1 mm [Elek et al. 2020], hence it is expected that those higher values of fit would have an impact on the breaking force for the corner joints.

In the case when the beams are joined immediately after the joints have been made, shrinkage occurs in the joined beams (frames). Then stresses occur inside the joint on the gluing line, which contribute to faster destruction of the joint, that is, they reduce the load-bearing capacity of the joint itself. The stresses that occur inside the glue make the joint crack exactly along the gluing line during loading.

Table 2. Processing accuracy values

Group number	Beam	Moisture before conditioning (%)	Arithmetic mean of measured thickness [mm]	Moisture after conditioning (%)	Arithmetic mean of proposed thickness after conditioning [mm]	Coefficients of variation
1	Horizontal	12	10.5	12	10.5	0.6097
	Vertical	12	9.98	12	9.98	0.5557
2	Horizontal	12	10.3	12	10.3	0.4649
	Vertical	18	9.95	12	9.76	0.5591
3	Horizontal	18	10.3	12	10.5	1.2640
	Vertical	12	9.96	12	9.96	0.3280

It is a known fact that with the change in moisture in the hygroscopic area, wood changes its properties [Šoškić and Popović 2002], which was confirmed in this test as well. The obtained results showed that the joints with the lower initial moisture have higher strength. When comparing the average tested strength of the samples, the Group 1 samples had the highest value of 16.38 kN. Group 2 had an average strength of 16.04 kN, while that of Group 3 was 15.41 kN (Figure 6).

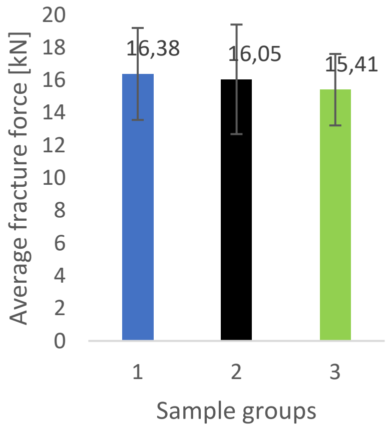

Fig. 6. Average value of fracture force for sample groups

In comparison to the results given by [Pantaleo, Ferri, and Pellerano 2014], these forces are about 20% higher. It is probably due to the different outside profile of the window and lower gluing area. Moreover, the tenon and mortise joint [Prekrat et al. 2014] obtained lower values for corner strength because of similar reasons. The results given by [Hrovatin et al. 2013] are also lower because of the different cross section and joint type (with a wooden ring). These samples obtained about a third of the breaking force values that were achieved by PVC windows [Postawa, Stachowiak, and Gnatowski 2017].

Statistical analysis of the results was conducted in the SPSS v.20 program in three steps. Firstly, all the results were tested for normality. After corrections for outliers, it was determined that all three groups follow normal distribution (p_1=0.306; p_2=0.769 and p_3=0.306). Then, t-tests were carried out for all the group combinations (1-2, 1-3 and 2-3). There was no significant statistical difference between Groups 1 and 2 (p=0.344), yet there was a significant statistical difference between Groups 1 and 3 (p=0.007) and Groups 2 and 3 (p=0.001). In the end, the statistical analysis using the ANOVA method showed there were no significant statistical differences between any of the groups (p=0.296).

Observing the average fracture values for all the three groups of samples, there is a difference in the strength of the angular joints. Namely, the Group 1 samples made from beams that were dried to the recommended moisture content of 12 ± 2% were expected to have the highest strength. Among the other groups, Group 2 (horizontal beam samples with a moisture content of 12 ± 2% and vertical beams with a moisture content of 18 ± 2%) obtained a higher average value of joint strength than Group 3 (vertical beam samples with a moisture content of 18 ± 2% and horizontal beams with a moisture content of 12 ± 2%). This distribution of results was expected before the study, however, the difference between the obtained results of the groups is smaller than expected. The deviation of this difference from the expected value was because it was originally planned to test the samples at the moisture content of the beams that they had at the time of making the window frames (12 ± 2% and 18 ± 2%). Nevertheless, during the research it was concluded that this does not reflect the real conditions in which the mentioned product (window) will be used. From the moment of the production of the window frame until the moment of its installation in the building, a certain time will pass, which is long enough for the moisture of all the beams within one frame to equalize and reach the moisture of operating conditions (12 ± 2%). Therefore, before testing the samples they were conditioned to the mentioned moisture content (12 ± 2%). Furthermore, the used PVA-c adhesives are designed in such a way (with increased elasticity) to be able to cover a wide range of wood moisture (6-20%) with a small loss of the prescribed properties.

In relation to the control group (Group 1 samples), the other two groups do not have excessive deviations (Group 2 ≈5.43% difference, Group 3 ≈8.9%). Nonetheless, if this difference is observed from the point of view of the durability and strength of the product itself (Groups 2 and 3 have lower strength by about 40-100 N than the control group), potential problems can be noticed.

It is necessary to conduct further research on how such joints behave over a longer period (a period longer than 10 years). Owing to the constant influence of weathering and the rheological properties of wood, it can be assumed that the mentioned difference in joint strength will have an impact on the overall window quality. From an economic point of view, the cost of energy loss would only increase over time.

Conclusions

The paper investigates the influence of the change in moisture content on the strength of corner joints in windows. The strength of the joint due to the change in the moisture content of one of the beams was analyzed. While analyzing the papers published to date, it was concluded that there are generally relatively few papers that have been published in the last three decades in the most available electronic journals in this field. Another shortcoming is the lack of norms that regulate this area. Upon review of the published standards, as well as the standards that are in the phase of revision and preparation, it was concluded that there is no standard that regulates the area of testing the angular strength of wooden windows.

The highest average strength of the corner joint was exhibited by the beams of the first group (16.38 kN), where the beams were dried according to the instructions from the literature. The samples of this group did not experience added internal stresses in the joint during the conditioning phase. The other two groups had a somewhat lower average strength (Group 2 16.05 kN and Group 3 15.41 kN). The t-tests revealed that there were significant statistical differences when comparing Groups 1 and 2 to Group 3. The reason for this most probably lies in the position of the beams with the higher moisture content. Namely, the vertical beams are the ones where the mortises are made and as such are subject to higher dimensional change with a change in the moisture content (from 18% to 12%). This is probably the reason that led to the lower average strength of the corner joint. The ANOVA test showed that there were no significant statistical differences when comparing the average strength of all the groups. With this in mind, it can be safely assumed that there would be no great difference in the corner joint strength if all the beams were dried between a 12% and 18% moisture content. For the best results, all the beams should be dried to a 12% moisture content. In addition, the closeness of fit should be kept at the optimal value of 0.1 mm in order to achieve higher breaking forces. For this reason, it is advisable not to use beams with extreme values of moisture content (12% and 18%) in the same window. It is rather advisable to use beams with a smaller moisture content difference, i.e. 12-14% or 14-16% or 16-18%.

To further expand on this problem, it would be interesting to repeat the experiment with the participation of the aging process under load in controlled climatic operating conditions. Also, the economic aspects could be used as a factor to determine whether drying to 12% moisture content is really economically justified. The obtained results of the strength of the angular joints from this research should be used as a starting point for further research on this topic.

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