Agronomy Research **16**(4), 1677–1685, 2018
https://doi.org/10.15159/AR.18.193

Effect of environmental temperature on bending strength of the finger jointed aspen lumber

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Abstract. Glued sauna wall boards are used as non–load–bearing structures. These products are subject to aggressive microclimate impact and very often for the gluing in length and width thermoplastic polyvinyl acetate adhesives (PVAC) are used.
In the performed research sauna wall boards made of common aspen (*Populus tremula* L.) with mean wood moisture content 8% were used. For the gluing in length with finger joint PVAC glue of D4 (LVS EN 204) group was used.
The aim of the research is identifying the impact of the environmental temperature on the strength of finger jointed aspen timber in 4 point static bending (in compliance with standard LVS EN 408). As a result of the study it was established, that after holding the finger jointed testing pieces visible in flat wise for 3 hours at the temperature of 100 °C, the mean bending strength decreased by 56% or 31.7 MPa in comparison to that held in the standard atmosphere. In case of the aspen timber with finger joints visible in edge wise held for 3 hours at the temperature of 100 °C, the bending strength decreased by 60% or 29.3 MPa in comparison to the testing pieces of the same type held in the standard atmosphere.

Key words: thermoplastic glue, sauna wall board, temperature effect.

INTRODUCTION

Glued timber has experienced a major growth of consumption during the last 15 years. The main reason for this is the availability of raw materials, the low energy consumption of the production process and the attractive price of the end product. Glued timber has turned from being just a decorative material into broadly used basic structural material with essential advantages in comparison to steel or concrete (Kociņš, 2007). The popularity of wood gluing can be explained by its several essential advantages, for example, the increased sizes in all directions and possibilities to produce different 3D structural building elements – curved, twisted etc. The possibility of constructing robust connections minimising deformations of the elements to be connected presents another essential advantage. Also timber materials of small dimensions and lower quality can be used for production of glued structures. Irrespective of the natural dimension of timber, glued structures of virtually unlimited cross section, any rational profile and length can be produced. Maximum mechanisation of the technological process, convenient transportation of glued materials and their low weight complies with the modern construction requirements (Ulpe & Kupče, 1991).

The finger joints are better than the slope connection which is usually applied for gluing of plywood and peeled veneers. For stretched and bent elements the finger joint is more secure as the glued surface area is bigger. However, in the finger joints mainly shear stress and minor tension stresses can be found. The contact is constructed based on the assessment that the stress levels in the glue would not reach the ultimate strength before timber reaches it. By using the finger joints the timber can not only extend, it can also be connected under an angle (Ulpe & Kupče, 1991).

Geometric parameters of finger joints (Fig. 1) and dimensions of the material have a considerable impact upon the strength of the finger joints (Thelanderson & Larsen, 2003). In the elements of non–load–bearing structures PVAC glues which are resistant to temperature up to 110 °C and even up to 145 °C when modifications are most often used, moreover, if the two-component dispersion glue is used. The connections of PVAC glue do not dissolve in water, however, they swell and lose their strength considerably. Humidity and water resistance depends on the chemical composition of glues (Kūliņš, 2004). PVAC glues are physically hardening glues with high adhesion and, depending on application, they are characterised by high strength in both dry and very wet service conditions. Plasticisers from 10 to 50% can be added to PVAC glues. They maintain flexibility of the glue connection even at low temperatures (Zeppenfeld & Grunwald, 2005).

Similar to increase of moisture content in timber, increase of timber temperature decreases the mechanical properties. It is important to investigate the mechanical properties of timber as the timber temperature increases. However, from the point of view of drying it is important to identify the mechanical properties as the timber moisture content decreases within the temperature range from 10 to 140 °C. In order not to decrease the mechanical properties of timber without causing the chemical destruction of timber, at the timber moisture content of 70% and above the temperature may not be increased above 45 °C. Along with the temperature increase, the moisture conductivity increases considerably. When temperature increases from 20 to 60 °C and then up to 80 °C, the moisture conductivity rate in tangential direction for fibres increases, and in case of aspen wood this increase is 3.8 and 7.1 times (Tuherm, 2007). However, if the temperature increases above 40 °C, the stability of the glue connection decreases considerably. Chemical reactions of the timber take place under the impact of moisture and temperature. The lower the moisture the higher the temperature may be without reducing the mechanical properties of timber. Moisture and temperature are closely interacting. At a constant moisture content and temperature lover than 150 °C, mechanical properties are approximately linearly related to temperature (Wood Handbook, 2010). Also Peter Niemz and Walter Ulrich Sonderegger carried out that increased temperature are decreasing the mechanical properties of wood (Niemz & Sonderegger, 2017). The reduction of strength is also affected by duration when timber is kept in the environmental temperature. Repeated drying and moistening of timber also have a negative impact on the physical and mechanical properties of timber. As well the temperature impact is one of the most important properties of glued timber elements

(Sedliačik & Šmidriaková, 2012). Previous research made by authors Ján Sedliačik and Mariá Šmidriaková (Sedliačik & Šmidriaková, 2012) shows that bending strength of glued finger joints made out of beech (*Fagus sylvatica* L.) and spruce (*Picea abies* L.) with 1-component polyurethane (PUR) and 2-component melamine–urea–formaldehyde (MUF) glues at increased temperature up to 110 °C, decreases.

From the point of view of the national economy, in Latvia aspen is the timber with the highest potential following pine, birch and spruce. It has the best application when it is used for interior finish of sauna, as well as other interior finish works and structures with humidity up to 15%. Aspen has a shorter lifetime in outdoor conditions. Aspen is characterised by the lifetime which is among the longest ones if the moisture content does not exceed 9%. Considering the practical operational conditions, aspen is the species of timber with lowest resistance to biological impact, following linden. It is characteristic for aspen that at the age of cutting 40% of aspen has been affected by rot (Tuherm, 2007). Aspen timber can be used for sauna wall board thanks to its low density. Due to its low density, aspen has high heat capacity, however, comparatively low heat conductivity. Last couple of year's sauna wall board production companies are trying to fulfil requirements of the customers to make longer and wider wall boards with higher quality surface. The lower quality of aspen timber requires to glue these elements in length, width and height. Due to health hazards in formaldehyde emissions from glues with base of these, there is one possibility to use PVAC glues for common products (Sedliačik & Šmidriaková, 2012).

The aim of the research to investigate the influence of the environmental temperature to the finger jointed aspen lumber glued with PVAC glue.

MATERIALS AND METHODS

The dimensions of the cross section of produced aspen (*Populus tremula* L.) lumbers were 28×74 mm. They were industrially dried till moisture content 8%. Glued products of this type are used for production of sauna wall and cladding boards. After drying, all the visually identified defects of wood were cut out (cracks, knots and rot), thus obtaining defect–free lumber with the nominal length of 700 mm and was cut in half. Before finger joints and jointing were made, from connection side of finger joints of the each lumber specimen was cut for identification of the moisture content and density. At the ends of lumber finger joints were industrially produced. For one part of the testing pieces finger joints was visible in the flat wise and for the other part in the edge wise (Fig. 1) (Jokerst, 1981).

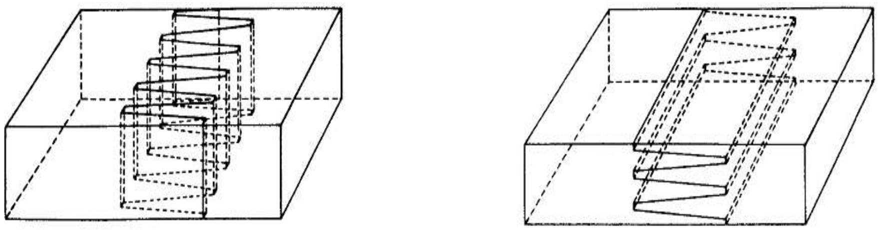

Figure 1. View of Finger Joints: 1 – flat wise; 2 – edge wise (Jokerst, 1981).

As both parts of the glued lumber elements were produced from the same aspen lumber, the impact of the differences of moisture content and density of different lumber in bending strength of the glued finger joints has been minimised.

Production of finger joints is based on the operational properties of the selected products. The rated geometric parameters of produced finger joints and testing piece are presented in (Fig. 2).

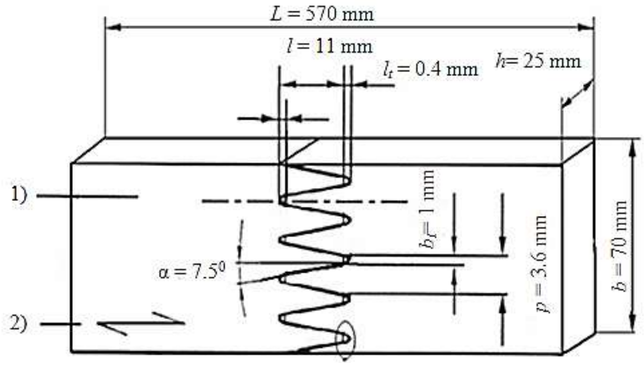

Figure 2. Linear and angle parameters of the finger joint: l – length of fingers; p – step of fingers; b_t – width of the finger; l_t – tolerance of the finger joints end; α – side angle of the finger joint; L – length of testing piece; h – thickness of the testing piece; b – width of the piece; 1) – way of symmetry of the finger joint; 2) – fibre direction of the testing piece (DIN68140EErl ND, 1981).

In the research polyvinyl acetate glue D4 group (EN 204) was used which is one component glue broadly used by wood processing companies for gluing window and door components. The method of application of glue was by soaking lumber elements and the glue consumption in testing pieces was identified by weighing for each individual testing piece. The scale with accuracy of 0.01 g was used for weighing the testing pieces.

The open holding time of lumber elements after application of glue was 15 to 20 seconds. The gluing surface area was identified for both the finger joints produced in the flat wise and it was 8,725 mm^2, as well as edge wise and it was 7,175 mm^2.

Within the developed research 75 glued testing pieces with finger joint in flat wise and 75 with finger joint in edge wise were produced. Also one group with 15 testing pieces with no finger joints as reference testing pieces was made for testing in standard atmosphere (air temperature 20 ± 3 °C; air humidity 65 ± 5%). For investigation of the influence of the environmental temperature to finger joint mechanical properties followed temperature levels 20, 40, 60, 80 and 100 °C were selected. For each of temperature groups 15 testing pieces were selected.

For gluing with finger joints, the laboratory hydraulic press was used after application of glue (Fig. 3). The pressing

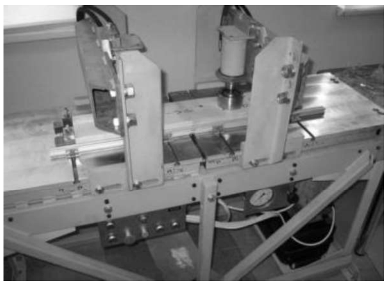

Figure 3. Equipment for gluing finger joints.

was done by first applying vertically slight pressure to the lumber element flat wise and then adding pressure horizontally from the both ends of the testing pieces. The total closed holding time was 30 seconds. Gluing of testing pieces was performed by the end pressure 1.7 MPa and the holding time in the press under the pressure for 2 seconds. The holding time was controlled by using a chronometer.

Testing pieces with finger joint visible on both the flat and edge wise, following their production and gluing, were stored for 168 hours in a conditioning chamber, under standard climate conditions at environmental temperature 20 ± 2 °C and relative air humidity 65 ± 5%, until stable timber moisture content and complete hardening of glue. Testing pieces were placed in the conditioning chamber after their marking by maintaining small distances between them to ensure air circulation around each testing piece. Following conditioning testing pieces divided into their preliminary treatment groups, were placed in heating ovens for starting heating.. Testing pieces were held at the above mentioned temperatures for 3 hours in order for heat to penetrate thoroughly. Testing pieces were placed in the oven with small distances between them in order to secure that heat penetrates throughout the whole cross–section of the material.

The reference testing pieces were produced from aspen lumber with the length of 570 mm, free of any visible wood defects (knots, splits and fibre distortion) in order to prevent any impact upon properties in testing. The initial moisture content of reference testing pieces was 8%. The reference testing pieces were conditioned at the standard atmosphere in a conditioning chamber until obtaining constant mass.

Following production of all the testing pieces and holding them under specific temperature, the mechanical properties were determined under four–point statistic bending in compliance with the requirements of standard LVS EN 408 (EN 408, 2003). It was done after taking out testing piece by piece from oven with specific temperature and test them in standard atmosphere and room temperature.

For all testing pieces both thickness and width was determined at the distance of approximately 40 mm from the finger joint by means of a sliding calliper with the accuracy of up to 0.1 mm. The measuring ruler with the accuracy 1 mm was used for determining the length of a testing pieces.

Investigation of the moisture content prior to gluing and at the moment of test was performed in compliance with the methodology of standard EN 13183–1 (EN 13183–1, 2003).

After investigation of testing pieces in bending, moisture content specimen were cut from them again in order to determine the difference of moisture after testing. Specimens for determining moisture content were cut as close as possible to the breaking place.

The same cut specimens used for determining moisture content were also used for determining the density of the specimens. The timber density prior to gluing and after drying was determined in compliance with standard ISO 13061-2 (ISO 13061-2, 2014).

The mean arithmetic values, standard deviations and the statistically significant correlations for sets of testing pieces and specimens were determined by using the statistic calculation methodology (Arhipova & Bāliņa, 2006). MS Excel software was used for summary and statistic processing of end results.

RESULTS AND DISCUSSION

The mean application of the glue for finger joints produced in the flat wise is 194 g m^{-2}, and for finger joints produced in the edge wise is 237 g m^{-2} (Table 1). By pressing the lumber elements together, more glue was pressed out from finger joints produced in the flat wise, which explains the reason why the glue application is lower.

Table 1. Glue application and physical properties (mean values and standard deviations) of tested pieces

Test/ Temperature groups	Mean density (standard deviation), kg m^{-3}		Mean moisture content (standard deviation), %		Mean glue application (standard deviation), g m^{-2}	
	Flat wise	Edge wise	Flat wise	Edge wise	Flat wise	Edge wise
Temp. 20 °C	458 (48)	464 (31)	8.2 (0.95)	7.8 (0.26)	198 (18.4)	238 (31.8)
Temp. 40 °C	453 (57)	465 (27)	8.8 (1.13)	7.9 (0.30)	198 (20.0)	239 (38.5)
Temp. 60 °C	449 (49)	471 (31)	8.3 (0.72)	7.9 (0.20)	187 (26.7)	230 (35.2)
Temp. 80 °C	448 (42)	445 (27)	7.7 (1.22)	8.1 (0.41)	191 (24.3)	233 (37.5)
Temp. 100 °C	436 (48)	464 (22)	7.6 (0.86)	7.9 (0.39)	198 (18.2)	242 (28.7)
Ref. solid wood	458 (72)		8.3 (0.72)		-	

The glue application was determined by weighing each testing piece prior to and after gluing. In both cases, when the produced finger joints are glued, the margins of optimum glue application as declared by the manufacturer were exceeded by gluing the material along the face and connected it along the thickness. As in case of the finger joints the end timber is glued, higher glue consumption than in case of gluing materials along thickness is permitted. Both on the flat and on edge wise the minimum and maximum glue application was determined. The minimum application is 140 g m^{-2} and the maximum application is 321 g m^{-2}. The statistically significant correlation between the glue application and the static bending strength for all ten groups was not found ($p > 0.05$).

Following conditioning under standard atmosphere, upon checking the reference testing pieces in four point bending, the obtained mean bending strength is 76.3 MPa. This value is used as the maximum bending strength value of the relevant material for comparing the other testing pieces.

In case of the finger joint visible in the flat wise of the testing piece, following conditioning under the standard atmosphere, the obtained mean bending strength is 57.1 MPa. As compared with the reference testing pieces (solid wood), they withstand up to 75% of the values of the bending strength of aspen reference testing pieces. In case finger joints are visible in the edge wise, the mean bending strength is 48.7 MPa. They withstand up to 64% of the values of the bending strength of aspen reference testing pieces (Fig. 4).

The temperature impact upon the bending strength aspen finger joints produced in the flat wise is presented in (Fig. 4).

There is a strict not linear functionally negative correlation between the environmental temperature and the bending strength of aspen finger joints produced in the flat wise and it is described by the logarithmic correlation coefficient 0.9.

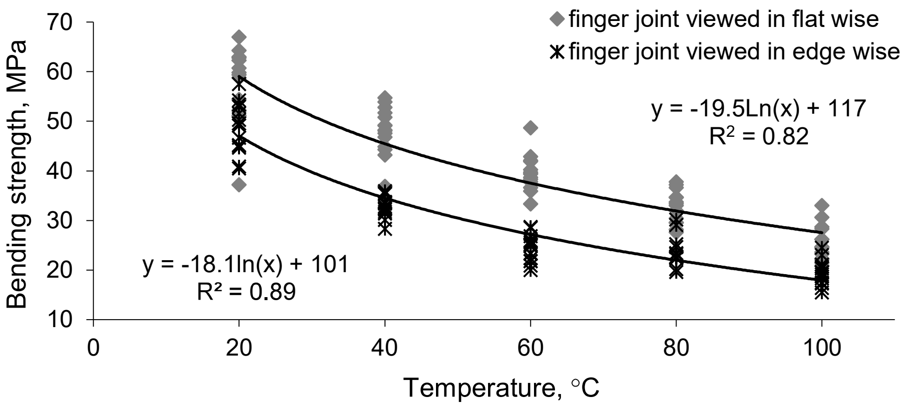

Figure 4. Temperature influence to bending strength of the aspen finger joints.

There is a strict not linear functionally negative correlation between the environmental temperature and the bending strength of aspen finger joints produced in the edge wise and it is described by the logarithmic correlation coefficient 0.9. As the environmental temperature of aspen finger joints increases, the bending strength decreases, both cases.

When sauna wall boards are longitudinally glued by using finger joints and PVAC, in case of both types of production of finger joints, under increased temperature (100 °C), a considerable decrease (exceeding 50%) of the bending strength should be expected in comparison to the bending strength of sauna wall boards under standard atmosphere.

Several conclusions can be drawn in the result of analysis of the impact of aspen density prior to gluing upon the bending strength of finger jointed aspen sauna wall boards. Following conditioning of testing pieces in the standard atmosphere, there is a medium strict and functionally positive correlation between the density and the bending strength of the finger jointed aspen sauna wall boards and it is described by the linear correlation coefficients 0.7 (in case of testing pieces with the finger joint produced in the flat wise) and 0.5 (in case of testing pieces with the finger joint produced in the edge wise). The strong correlation between the density and the bending strength for all ten groups was found ($p < 0.05$).

It follows from the above that if aspen timber with higher density is chosen for finger jointing of sauna wall boards, following conditioning of the glued material in the standard conditioning atmosphere, materials with higher bending strength will be obtained. In the result of analysis of density upon the bending strength of finger jointed sauna wall boards held in high temperature it can be concluded that there are weak correlations between the density of aspen timber prior to gluing and the bending strength of aspen sauna wall boards after holding them in high temperatures, the linear correlation coefficients being below 0.5. In the result of comparing the bending strength of sauna wall boards at holding temperature levels 20 and 100 °C, it can be seen that the impact of aspen timber density upon the bending strength of finger jointed lumber tends to decrease. In case of both type of production of finger joints, following holding in temperature of 100 °C, a trend can be seen that as aspen timber density prior to gluing increases the bending strength decreases.

Based on the results of the research, we can conclude that temperature impact to the aspen finger jointed wall boards glued with PVAC are showing the same tendencies as it is described in previous research where PUR and MUF glues were used, increased temperature up to 110 °C decreasing the bending strength of finger jointed spruce wood (Sedliačik & Šmidriaková, 2012). Within carried research this type of the PVAC glue had to be considered separately, as it is classified as thermoplastic glues used for non–load–bearing structures.

Results of research done by institute ETH Zurich has shown strength reduction differences if using adhesives that fulfil current approval criteria for the use in load-bearing timber components (Frangi et al., 2012). Sauna wall boards elements are not classified as load – bearing timber components, but even using there are used under short term loads, it could be recommend to use that type of glue for that kind of application.

CONCLUSIONS

1. The outcome of research shows that glued joints may be the weakest points of finger jointed aspen sauna wall boards under conditions of increased temperature.
2. Regression diagrams of bending strength of the tested finger joints (visible in flat or edge wise), glued with PVAC glue, in the both cases shows no linear tendencies when environmental temperature increases from 20 to 100 °C.
3. The thermoplastics glues can be used for finger jointing of aspen wood in case the environmental temperature of the used connections don't increases more than 80 °C, in other case bending strength of connection decreases more than 50%.
4. In order to obtain materials with a higher bending strength, following conditioning of longitudinal glued material in the standard atmosphere, aspen timber with higher density should be chosen, strong correlation between the density and the bending strength for all ten groups was found ($p < 0.05$).
5. For sauna wall elements with higher bending strength, finger joints viewed in flat wise should be used, for less visible joints, finger joints viewed in edge wise should be used. For investigation of influence of the temperature to the finger joints for several cycles weathering tests should be done.

ACKNOWLEDGEMENTS. Research was carried out within the project 'Technology validation of the latest bonding and decorative, protective treatment for high value-added wood products production', Central Finance and Contracting Agency (CFCA), project No. 1.2.1.1/16/A/009 co-financed by the European Union within the Project framework of the European Regional Development Fund.

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