# Heat Resistance of Glued Finger Joints in Spruce Wood Constructions

Martin Sviták,[a] Miroslav Gašparík,[b,]* and Jan Penc [a]

The heat resistance of glued spruce wood was evaluated for different joint types and adhesives. Bending strength, modulus of elasticity, and also fracture evaluation were investigated on glued spruce samples made by the finger-jointed principle. Finger-jointed samples were glued with polyurethane (PUR) and melamine-urea-formaldehyde (MUF) adhesives. Heat loading was realized at temperatures 60, 80, and 110 °C and compared with wood with 20 °C. A static bending test with four-point flexural test was used. Elevated temperature and adhesive type had an important influence on the bending strength. On the other hand, adhesive type had a significant influence on the modulus of elasticity, but elevated temperature had no substantial influence.

*Keywords: PUR adhesive; MUF adhesive; Temperature; Bending strength; Modulus of elasticity; Spruce wood; Heat resistance*

*Contact information: a: Department of Wood Products and Wood Constructions, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521 Czech Republic; b: Department of Wood Processing, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521 Czech Republic; *Corresponding author: gathiss@gmail.com*

## INTRODUCTION

Humidity is an essential factor that can reduce the strength of the structural elements. However, the structures may also be exposed to other influences that also disrupt the integrity of the connection of individual elements. Elevated temperature is one of such factors.

Laminated elements (*e.g*. LVL) are frequently used in construction (Gaff and Gáborík 2014) but are not suitable for bonding by mechanical joints. On the contrary, the elements of native wood are suitable for such joints. Finger joints are an essential type of joint frequently used in construction or furniture industries. Two different types of finger joints can be used, namely non-structural and structural. Non-structural finger joints have shorter fingers (pins) and are used mainly for furniture. However, the structural finger joints (Fig. 1) have longer sharp, almost pointed pins and ensure the strength needed for flooring, roof, and other aspects of construction (Vrazel and Sellers 2005).

Thanks to the finger joint it is possible to use also smaller pieces of wood, and thus obtain a material with good mechanical properties. Individual pieces of wood fitted with finger joints are connected to each other in the longitudinal direction and then transformed into finger-jointed lumber. Finger-jointed lumber is the type of material that has the potential to have strength properties as good as solid wood. However, this potential is realized only if the joint is made of a suitable type of wood, with the optimum dimensions of fingers (pins), and the type of adhesive. Therefore, this material has been studied by many authors, *e.g*. Schober and Spatt (1993), Smardzewski (1996), Bustos *et al*. (2003), Bustos *et al*. (2004), and Vassileiou (2011).

Finger-jointed lumber or structural beams during their lifetime in construction may get into a situation where they are loaded at elevated temperature (mostly from 50 °C to 220 °C) and compared with ambient temperature 20 °C. The issue of the impact of elevated temperatures on structural wood or finger jointed lumber has been studied in some works. Sedliačik and Šmidriaková (2012) have dealt with heat resistance of glued finger joints at 20, 50, 80, and 100 °C, and described a decrease in bond strength depending on the temperature increase. Frangi *et al*. (2012) examined the influence of temperature (20, 40, 100, and 140 °C) on the fracture characteristics. They found that the fracture characteristics and strength at elevated temperatures and during tension stress are strongly influenced by the behavior of the adhesive itself, and therefore may affect the proposals for of fire resistance of glued wood.

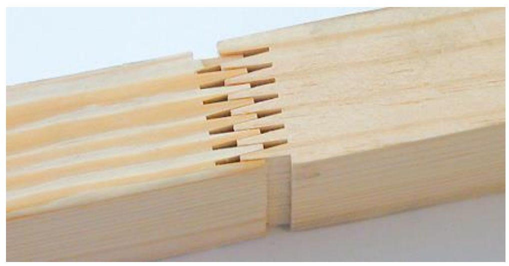

**Fig. 1.** Structural finger joint

Källander and Lind (2001) analyzed the strength of glued wood before and after the fire resistance test of polyurethane (PUR), urea formaldehyde (UF), polyvinyl acetate (PVAc), and emulsion polymer isocyanate (EPI) adhesives. Their results showed that the type of adhesive had little influence on the resistance of the joint at elevated temperatures during fire. They also found no correlation between burning out and lowering of the shear strength. Falkner and Teutsch (2006) reported that under glass facades in direct sunlight, the temperature may rise up to 60 °C; this can cause increased thermal load of glued finger joints, which may result in construction failure. During a fire, the temperature in the outer parts of the beam can reach above 100 °C. In deeper layers, due to the low thermal conductivity of the wood, the temperatures are typically significantly lower. Delivered energy is also partially consumed for the evaporation of bound water from wood.

The influence of temperature on the bonded elements has also been examined by George *et al.* (2003) and Na *et al*. (2005). They demonstrated the greatest impact on PUR adhesive was in the temperature range of 40 to 80 °C, while Richter *et al*. (2006) found that this phenomenon can be removed with a higher proportion of isocyanate, which will improve initial strength.

The aim of this work was to verify and evaluate the impact of temperature on fracture with respect to the type of glued finger joints for spruce construction elements, which were bonded by using two kinds of adhesives. The heat loading was performed at temperatures of 60, 80, and 110 °C, and the results were compared with 20 °C. The main monitored criterion was bending strength together with the determination of the modulus of elasticity.

## MATERIALS AND METHODS

### Materials

Seventy-five-year-old European spruce trees (*Picea abies* L.) harvested near Kostelec nad Černými lesy, east of Prague, were used for the experiments. Suitable zones were cut from the trunk at a height of 1.5 m from the stump. The zones were cut into boards with dimensions of 50 × 150 × 620 mm. Then the boards were cut into smaller pieces 50 × 150 × 300 mm, from which have been cut off slices to determine the moisture content and density according to standards EN 13183-1 (2002) and ISO 3130. Then pieces were pre-dried in an oven chamber to a 15% moisture content. Finger joints were created by horizontal milling cutter at the ends of these defect-free pieces in accordance with EN 385 (2001). Figure 2 shows the dimensions of the finger joints.

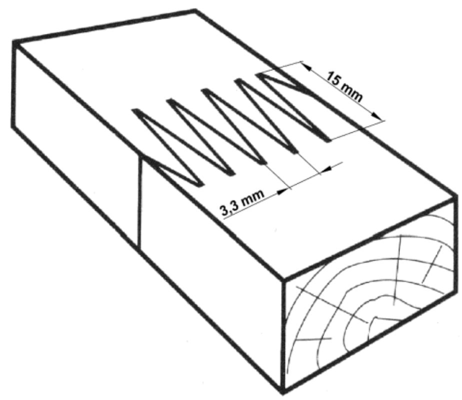


**Fig. 2.** Dimensions of finger joint

Subsequently, one group of samples was glued with the polyurethane (PUR) adhesive Kestopur 1030 (Kiilto; Finland), while the second group was glued with the melamine-urea-formaldehyde (MUF) adhesive CASCOMIN 1247 (CASCO Adhesives AB; Sweden). Both adhesives meet the requirements of EN 301 (2006), EN 302-1 (2013) and 302-2 (2013) for bonding of wood structure elements by finger jointing and also for laminated wood. The specific properties of used adhesives are listed in Table 1.

**Table 1.** Specification of Adhesives

| Adhesive type | Chemical composition (according to EN 301) | Free-formaldehyde content (%) | Density ($kg/m^3$) | Adhesive spread ($g/m^2$) |
|---|---|---|---|---|
| PUR | One-part adhesive, type I. | none | 1247 | 150 - 350 |
| MUF | Two-part adhesive, type I. | 0.5 | 1200 | 150 - 300 |

Clear samples of finger-jointed lumber, with dimensions 30 × 120 × 570 mm, were conditioned in a conditioning room (moisture content ($\phi$) = 65 ± 3% and temperature ($t$) = 20 ± 2 ºC) to achieve equilibrium moisture content (EMC) of 12%. The samples were conditioned for more than two weeks before testing.

The entire study consisted of 48 samples, 6 samples per combination of adhesive type and temperature.

## Methods

*Heat loading*

Thermal loading was aimed to determine the effect of elevated temperature on the bending strength of glued joints. The heating chamber was preheated each time to the desired temperature (± 2 °C) before inserting the sample. The samples were heat-loaded in the thermal chamber UF450 (Memmert GmbH + Co. KG; Germany), at a given temperature (60, 80, and 100 °C), for a period of 120 ± 2 min. The samples tested at 20 °C served as the reference and were not heat-loaded (Penc 2011). The procedure of heat loading was conducted in accordance with standards EN 408 (2004) and EN 14257 (2006).

*Static bending*

The samples were bent by the free-bending principle (*i.e.*, four-point bending test) according to EN 408 (2004) (Fig. 3) immediately after the removing from heat chamber. The bending was carried out in a universal testing machine TT2850 E22 (TIRA; Germany) that contained a data logger for recording the maximum loading forces at the breaking point. Test samples were placed on supporting pins (*18h=>18*30=540 mm*) so that loading forces acted in the perpendicular direction considering the length of the sample, and a load was applied until they broke.

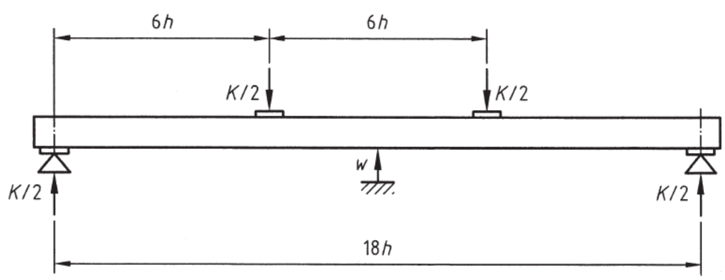


**Fig. 3.** Test arrangement for measuring global modulus of elasticity and bending strength

*Measurements*

The values of maximum loading forces were directly downloaded from the data logger on a personal computer, and the bending strength (*MOR*) and modulus of elasticity (*MOE*) was calculated. The increment of deformation (deflection), measured at the midpoint of the test sample (mid-span deflection), had an accuracy to 0.01 mm by a digital indicator gauge.

The dimensions of the samples, were measured with a digital caliper 500-150-20 (Mitutoyo; Japan) to a precision of 0.1 mm.

After breaking of sample the resulting fracture area (finger joint) was photographed and visually analyzed. A similar method was also used by Frangi *et al.* (2012). Cross-section of each fracture area was divided into 40 parts; each part represents 2.5% of this area (Fig. 4).

The percentage evaluation was conducted according to three criteria:

- S - fracture (breach) of the sample in the bond line,
- G - fracture (breach) of the sample at the root of fingers,
- A - fracture (breach) of the sample out of glued joint.

**Fig. 4.** Principle of visual evaluation of fracture area

*Calculations and evaluation*

The influence of factors on the bending strength and maximum deflection was statistically evaluated using ANOVA analysis, mainly by Fisher's F-test, in STATISTICA 12 software (Statsoft Inc.; USA).

The bending strength (MOR) of the samples was calculated after bending. These calculations were carried out according to EN 408 (2004) and Eq. 1,

$$f_m = \frac{l_s * F_{max}}{2\left(\frac{bh^2}{6}\right)} \tag{1}$$

where $f_m$ is the bending strength of wood (MPa), $F_{max}$ is the maximum (breaking) force (N), $l_s$ is the distance between loading position and the nearest support (mm), $b$ is the width of the test sample (mm), and $h$ is the height (thickness) of the test sample (mm).

The modulus of elasticity (MOE) of the samples was calculated after bending. These calculations were carried out according to EN 408 (2004) and Eq. 2,

$$E_{m,g} = \frac{l_0^3(F_2 - F_1)}{bh^3(w_2 - w_1)}\left[\left(\frac{3l_s}{4l_0}\right) - \left(\frac{l_s}{l_0}\right)\right]^3 \tag{2}$$

where $E_{m,g}$ is the global modulus of elasticity in bending (MPa), $F_2$-$F_1$ is the increment of load (force) on the straight-line portion of the load deformation curve (N), $w_2$-$w_1$ is the increment of deformations/deflection corresponding to $F_2$-$F_1$ (mm), $l_s$ is the distance between loading position and the nearest support (mm), $l_0$ is the span/distance between supporting pins (mm), $b$ is the width of the test sample (mm), and $h$ is the height (thickness) of the test sample (mm).

Density was calculated according to ISO 3131 (1975) and Eq. 3,

$$\rho = \frac{m}{h * b * l} = \frac{m}{V} \tag{3}$$

where $\rho$ is the density of the test sample (kg/m$^3$); $m$ is the mass (weight) of the test sample (kg); $h$, $b$, and $l$ (the height, width and length) are dimensions of the test sample (m); and $V$ is the volume of the test sample (m$^3$). The test samples for density measurement were cut off from the middle part of samples for bending. The dimensions of these test samples were in compliance with standard ISO 3130.

The moisture content of the samples was determined before and after testing. These calculations were carried out according to EN 13183-1 (2002) and Eq. 4,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{4}$$

where $w$ is the moisture content of the samples (%), $m_w$ is the mass (weight) of the test slice at certain moisture $w$ (kg), and $m_0$ is the mass (weight) of the oven-dry test slice (kg).

Drying to an oven-dry state was performed according to standard EN 13183-1 (2002). First, the test samples were cut to slices for moisture content measurement. Test slice were cut of full cross section and minimum 20 mm dimension in the direction of the grain from either end of the sample (before testing), or near the mid-point of the sample as close as possible to the breaking area (after testing). Then, testing slices were weighed and then dried at a temperature of 103 ± 2 ºC. Slices reached constant moisture content when the weight change between two weightings at intervals of 2 h did not exceed 0.1% of the mass of the slice.

## RESULTS AND DISCUSSION

### Physical Properties

The basic physical properties of wood are listed in Table 2. The EMC values of spruce finger jointed wood correspond to moisture content under conditions of $\varphi = 65 \pm 3\%$ and $t = 20 \pm 2$ °C. Average moisture content of finger jointed wood before testing was in range 10.5 to 12.41%. After testing, the moisture content was decreased to 6.5 – 6.9%.

The average initial density of spruce wood was 414 kg/m$^3$. This value corresponds to the 420 kg/m$^3$ indicated by Mayes and Oksanen (2003) and 422 kg/m$^3$ found by Brandner *et al*. (2007), while Repola (2006) found lower density, *i.e.* 385 kg/m$^3$.

On the other hand, the density after heat loading was lowered only slightly, up to 3%. Final average densities were 410.9, 407.3, and 402.1 kg/m$^3$ at 60, 80, and 110 °C.

### Bending Strength

Table 2 shows results from the statistical analysis, which presents the influence of factors on the bending strength of spruce wood. The results revealed that all factors were statistically significant ($p < 0.05$).

**Table 2.** Influence of Factors on Bending Strength

| Monitored factor | Sum of squares | Degree of freedom | Variance | Fisher's F - Test | Significance level P |
|---|---|---|---|---|---|
| Intercept | 70,313.22 | 1 | 70,313.22 | 1,247.974 | 0.000 |
| Adhesive type | 1,072.84 | 3 | 357.61 | 6.347 | 0.001 |
| Temperature | 296.27 | 1 | 296.27 | 5.258 | 0.027 |
| Adhesive type * Temperature | 523.63 | 3 | 174.54 | 3.098 | 0.037 |
| Error | 2,253.68 | 40 | 56.34 | | |

Statistical significance was evaluated at the 95% confidence interval

Due to the statistical results for the glued finger joints, it can be concluded that the greatest influence on the decrease of bending strength was heat loading, *i.e*. elevated temperature. Figure 5a shows a noticeable decrease between control samples with a temperature of 20 °C and elevated temperatures 60, 80, and 110 °C. Comparison of the samples with a different type of used adhesives indicates that the bending strength was higher in the finger joints with MUF adhesive (almost 41 MPa), whereas PUR samples showed a bending strength of 36 MPa (Fig. 5b).

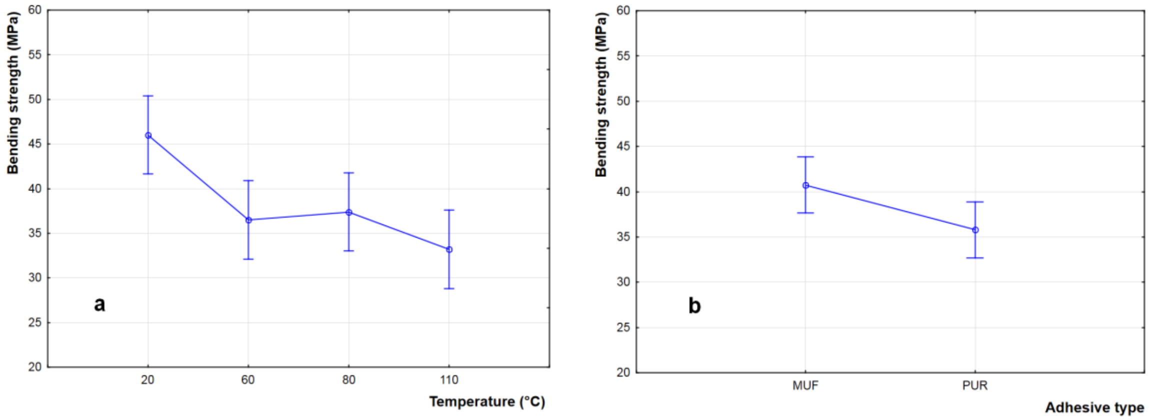


**Fig. 5.** Influence of (a) temperature and (b) adhesive type on bending strength

Figure 6 clearly shows that the samples with MUF adhesive had a linear decreasing trend. It is evident that the bending strength of adhesive joint decreased with increasing temperature, and very significantly (from 50 MPa to 31 MPa). Samples of PUR at 60 °C achieved a greater decrease of bending strength relative to the reference group of 20 °C, than the other two groups. This difference is probably caused by greater grain angle and hidden defects in the wood. Kliger *et al*. (1998), who investigated the bending characteristics of sawn timber from fast-and slow-growing types of spruce using four-point bending, found a bending strength in the range of 30.9 to 48.4 MPa.

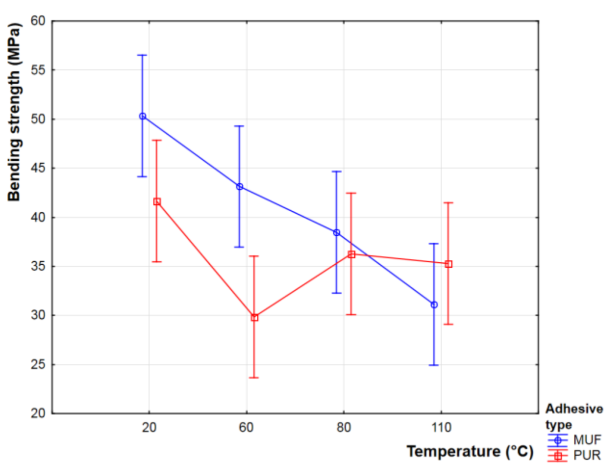


**Fig. 6.** Influence of temperature and adhesive type on bending strength

Overall, the decrease in bending strength can be explained by the basic characteristics of adhesives. Change of bending strength is partially caused by enhanced elasticity of the adhesive, rather than its degradation. This decrease of bending strength was not significantly increased at other higher temperatures because the thermal degradation occurs at temperatures above 110 °C.

It is possible to conclude that the strength of each group was influenced by many factors, among which can also be included the effect of temperature. In the present research it was found that even the highest temperature of 110 °C did not result in such damage to the joints, which would lower its strength below the minimum strength requirement according to EN 385 (2001), namely 24 MPa. König *et al*. (2008) investigated the influences of temperature for polyurethane adhesives and MUF at 20 °C and when exposed to fire. At 20 °C the bending strength of various adhesives showed no significant differences. When exposed to fire, the strength decreased by 70 to 80%. However, during an actual fire, much higher temperatures are reached than in the present case.

## Modulus of Elasticity

Table 3 shows the influence of factors and their interaction on the modulus of elasticity of wood. The results show that the influence of adhesive type was statistically significant ($p<0.05$), while the effect of temperature was not significant.

**Table 3.** Influence of Factors on Modulus of Elasticity

| Monitored factor | Sum of squares | Degree of freedom | Variance | Fisher's F - Test | Significance level P |
|---|---|---|---|---|---|
| Intercept | 4,484,390,723 | 1 | 4,484,390,723 | 984.6180 | 0.000 |
| Adhesive type | 153,536,410 | 1 | 153,536,410 | 33.7113 | 0.000 |
| Temperature | 11,880,040.3 | 3 | 3,960,013.42 | 0.8695 | 0.465 |
| Adhesive type * Temperature | 53,443,459.3 | 3 | 17,814,486,4 | 3.9114 | 0.015 |
| Error | 182,177,898 | 40 | 4,554,447.44 | | |

Statistical significance was evaluated at the 95% confidence interval

From the evaluation of elastic properties of the finger-glued joints it became clear that neither of temperature types indicated any influence on reducing of modulus of elasticity (Fig. 7b).

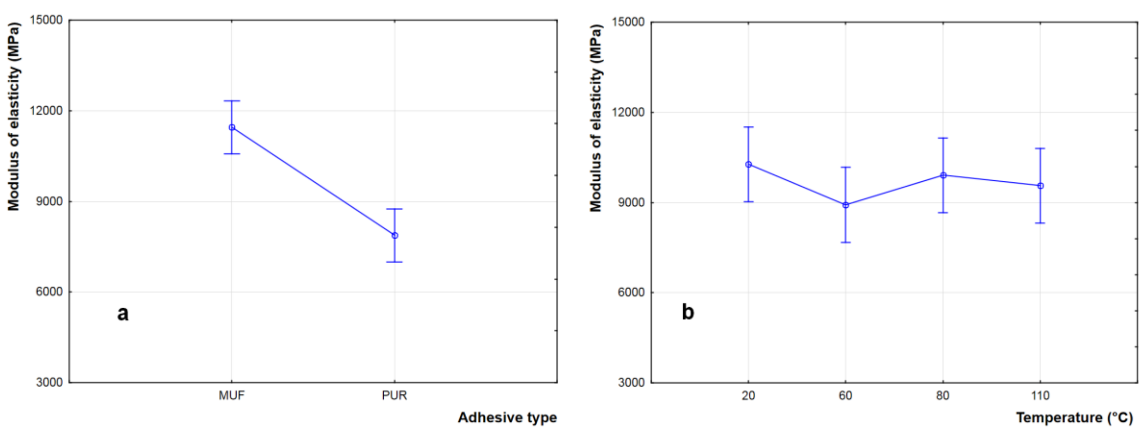


**Fig. 7.** Influence of (a) temperature and (b) adhesive type on modulus of elasticity

Some samples with low modulus of elasticity also had extremely high bending strength within the group. There was not any evident influence of modulus of elasticity on bonding strength. Also Karlinasari and Bahtiar (2011) confirmed a poor relationship between modulus of elasticity and bending strength. On the contrary, when comparing adhesive types (Fig. 7a), it was found that the elastic modulus reached higher values (up to 11 000 MPa) in the samples with MUF. This is due to the nature of adhesives applications, which can have a significant impact on just flexibility.

For the assessment limit states of structural elements, it is necessary to define the values for instantaneous and ultimate deformation of load by using the average values of the relevant modules of elasticity. Figure 8 shows that certain changes occur. In samples with MUF there was mostly a decrease with an increase in temperature, but this difference was not statistically significant.

Samples of PUR at 20 and 60 °C exhibited similar behavior as for bending strength, while at the temperatures of 80 and 100 °C there was an increase values of modulus of elasticity. The sharp decline in 60 °C could be caused by a hidden defect of wood, therefore the lower of average values were achieved.

Similar values of modulus of elasticity were indicated by Gong *et al.* (2009), who examined the finger joints on spruce wood, but with phenol-resorcinol-formaldehyde (PRF) adhesive, which achieved similar results as the bending properties as MUF.

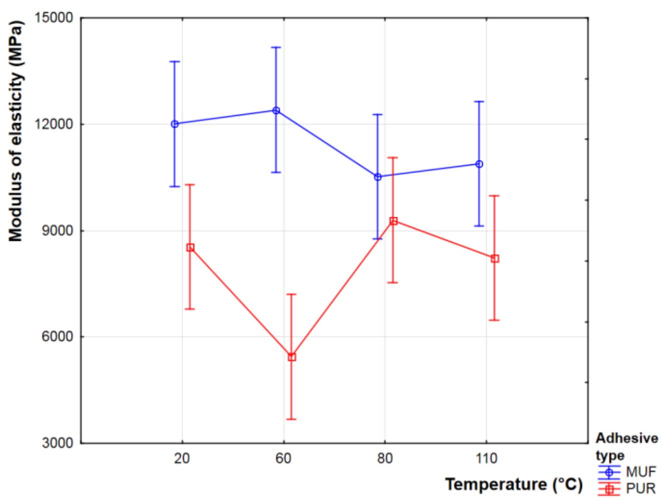


**Fig. 8.** Influence of temperature and adhesive type on modulus of elasticity

## Characteristics of Fractures

Due to the occurrence of several types of fractures, it was possible to compile Fig. 9, which indicates the average values of the percentage proportion of fracture in each group of samples.

Most samples contained a fracture in the bondline – S. The second most common type of fracture was breach at the root of fingers – G, and the least frequent was a fracture out of glued joints – A. This fact indicates that the damaged samples were made of good-quality wood, and only samples with PUR at 20 and 60 °C had a joint less strong than wood.

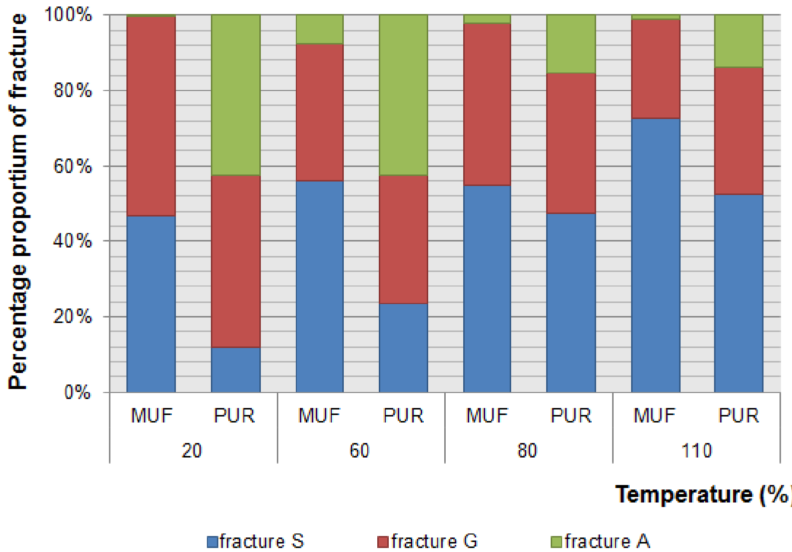


**Fig. 9.** Proportion of fracture types in finger joints

Table 4 summarizes the comparison of acquired values and shows prevalent type of fractures from average values.

**Table 4.** Percentage Proportion of Different Types of Fractures

| Testing Temperature (°C) | Adhesive type | Proportion of fracture (%) | | |
|---|---|---|---|---|
| | | S | G | A |
| **20** | **MUF** | 46.7 | **52.9** | 0.4 |
| | **PUR** | 12.1 | **45.4** | 42.5 |
| **60** | **MUF** | **55.8** | 36.7 | 7.5 |
| | **PUR** | 23.3 | 34.2 | **42.5** |
| **80** | **MUF** | **55.0** | 42.9 | 2.1 |
| | **PUR** | **47.5** | 37.1 | 15.4 |
| **110** | **MUF** | **72.5** | 26.3 | 1.3 |
| | **PUR** | **52.5** | 33.8 | 13.8 |

Samples with PUR had significantly higher proportion of fractures out of the joint than samples with by MUF (Table 4). This finding indicates a relatively strong joint with MUF adhesive and confirms the accuracy of the calculated values from the strength tests, as also demonstrated by Frangi *et al.* (2012).

From the analysis of fracture zones in all samples, it is clear that adhesive joints made with MUF did not show a greater proportion of fracture by pressure, because the fractures in bondline - S. PUR samples showed a characteristic fracture of the joints in the tension part (fracture of the sample at the root of fingers), with simultaneous shearing and breaking in the neutral axis of the sample. This can also be caused by multiple elastic properties of the adhesive type. Optimal adhesive joint is characterized by a distinctive strength. In our case, the type of fracture – A that represented this joint, but with the lowest occurrence.

## CONCLUSIONS

1. The bending strength of finger joints glued by MUF and PUR adhesives decreases with increasing temperature.
2. Modulus of elasticity exhibited little or no change with increasing temperature. Major changes were observed in the case of wood with MUF glue.
3. The results showed that the most common type of breaching due to the elevated temperatures is the fracture in the bondline. Breach of the wood out of glued joints occurred less frequently.

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