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HEAT RESISTANCE OF ADHESIVE JOINTS FOR WOOD CONSTRUCTIONS

TEPELNÁ ODOLNOSŤ LEPENÝCH SPOJOV PRE DREVNÉ KONŠTRUKCIE

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ABSTRACT

Heat resistance is one of most important properties of glued joints. The significance of this work consists in pointing out the fact that adhesive joints may be at conditions of increased temperature the weak points of the wood glued structure. The aim of this work is determination of relationship of the strength of glued joints at increased temperature determined as shear and bending strength of glued joints. The work describes strength properties of beech (*Fagus sylvatica* L.) and spruce (*Picea abies* L.) glued joints at thermal load at 20, 50, 80 and 110 °C. For gluing of wood samples, there were applied adhesives from two producers of 1-component polyurethane adhesives Jowapur 686.60 and Kestopur 1030, polyvinylacetate adhesive Duocoll 1050 D3 and 2-component melamine-urea-formaldehyde adhesive CASCOMIN 1247 with the hardener 2526. All types of adhesive systems showed a softening of the joints and also decreasing in shear and bending strength. Bending strength of glued finger joints at increased temperatures up to 110 °C always met the standard requirements.

Key words: adhesives, heat resistance, lap joint, finger joint, wood construction.

INTRODUCTION

Polyurethane (PUR) prepolymers are relatively new generation of reactive adhesives; they are liquid and high viscous resins at normal temperature. Hardening process runs at normal temperature, one component system crosslinks by reaction of free isocyanate groups with water molecules, urea bridges are formed in each intermediate stage (Sedliačik 2005). The thermal stability of adhesives for load-bearing construction has been one of their key parameters since engineered wood products were introduced in timber construction (Dudas, Jochim 2008, Štefko, Kuklík 2006). In the case of one-component moisture-curing polyurethane (1C PUR) adhesives, knowledge about relationships between their chemical structure and the resulting bonding properties is limited, especially under high-temperature conditions. The study by Clauss *et al.* (2011a) describes the structure property relationships of 1C PUR prepolymers, which were analysed in the temperature range from 20 to 200 °C by mechanical and rheological tests. NCO-terminated urethane prepolymers were prepared from systematically varied methylene diphenyl diisocyanate (MDI) and polyether mixtures. Bonded wood joints were tested for their tensile shear strength and polymer films were analysed by means of dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC). The results revealed a significant influence of hard segment content and cross-link density on the thermal stability of the prepolymers.

The relationship between the chemical structure of commercial polyurethanes and temperature-dependent creep properties was determined by RICHTER *et al*. (2006) in full scale tests and the results were compared with thermomechanical analysis. Comparison of mechanical performance with ^{13}C-NMR spectroscopy studies elucidated important structure-property relationships, which either allows the reduction or elimination of temperature-dependent creep in 1C-PUR adhesives for wood. The combination of the relative content of still reactive, free –NCO groups on the polyurethane, careful selection of the degree of resin polymerization and a slower rate of reaction are the three most significant parameters that have to be controlled to overcome the problem of temperature-dependent creep found in 1C-PUR adhesives. The results obtained indicate that adhesives presenting a combination of a higher content of still unreacted –NCO groups, a lower degree of polymerization and slower reaction rate are capable to counteract problems of high sensitivity of polyurethane to temperature-dependent creep.

Melamine-urea-formaldehyde resins (MUF) have been used successfully for wood products for three decades. Although wood products bonded by MUF resins have seen widespread use, formaldehyde emission from the products has become an indoor air pollution problem. It has been proposed that the more substituted triazine and urea nuclei in the MUF resin provide lower amounts of formaldehyde (TOHMURA *et al*. 2001); however the effect of the melamine content in MUF resins on the cured resin structure is still unclear. Melamine-formaldehyde (MF) adhesive showed excellent shear strength (CLAUSS *et al*. 2011b) at temperature range from 20 °C to 150 °C and even at 220 °C no discolouration of the bond line (caused by a thermal degradation) occurred. For urea-formaldehyde (UF) fracture surface, this degradation process occurred at much higher rate and it can be argued that the degradation process for MUF adhesives was delayed due to the addition of melamine. MUF adhesives were researched with thermomechanical analysis (TMA) in temperature mode between 40 °C and 220 °C by KAMOUNN, PIZZI (1998). Improvement in network tightness with the melamine salt resulted in higher strength of beech wood bonds.

For producing engineered wood products, different thermoplastic and thermosetting adhesives have been used. Polyvinyl acetate (PVAC) adhesives have a good bending property and water resistance and can be used in the production of structural and non structural wood products. Due to health hazards in formaldehyde emissions from formaldehyde based adhesives, there is growing interest in the usage of PVAC-based composites in furniture or residential construction. PVAC is one of thermoplastic adhesives that are mostly used as an emulsion. In order to improve the performance in adverse climatic conditions, PVAC adhesives are generally modified with cross-linking agents such as polymeric diphenylmethane isocyanate and other vinyl monomers during polymerisation. Cross-linked PVAC are rigid, better heat and moisture resistant. In the experiments, when testing tensile shear strength of PVAC adhesive joints after accelerated treatment, in some of cases, the average tensile shear strength of PVAC adhesive was increased slightly (SHUKLA *et al*. 2008). This was likely due to post-curing of the adhesive during accelerated treatment.

The thermal stability of glued wood joints is an important criterion to determine the suitability of adhesives in the field of engineered wood. Thereby the cohesiveness of the adhesive must not degrade under heat load. The current investigation by CLAUSS *et al*. (2011b) covers the influence of temperature from 20 to 220 °C on the shear strength of glued wood joints. Different adhesive systems were investigated. With increasing temperature, the shear strength of solid wood and also of glued wood joints decreased. There were big differences in thermal stability and failure behaviour between the adhesive systems as well as within the polyurethane group. The thermal stability of one-component polyurethane systems can be greatly varied by modifying their chemical structure. Well adapted one component polyurethane adhesives reach strength similar to that of phenol resorcinol resin.

CECEN *et al.* (2008) and TAVMAN *et al.* (2009) presented the study on the electrical conductivity, mechanical properties and adhesion properties of different adhesive systems filled with silver-coated wollastonite fibres. The wollastonite is frequently used in plastics applications because increases scratch resistance, thermal stability, welding strength, and decreases warpage and shrinkage. The results indicated that adhesives filled with W-Ag are materials with good mechanical properties.

The main aim of this research is determination of the thermal stability of lap and finger glued joints of wood constructions at various temperatures from 20 to 110 °C. Testing of shear strength of lap joints and bending strength of finger joints was carried out on samples of hard wood and soft wood species, beech and spruce.

METHODS

Used adhesive types, Jowapur 686.60 and Kestopur 1030 are 1-component, moisture curing polyurethane adhesives for joining of wooden materials. Both products meet the requirements of EN 301/302 standards stated at Norwegian Treteknisk Institute. Used adhesive Duocoll 1050 D3 is 1-component PVAC dispersion. Melamine-urea-formaldehyde adhesive CASCOMIN 1247 is 2-component resin with the hardener 2526. All used adhesives and a hardener were applied in a liquid state, the gluing process of samples was carried out according to adhesive manufacturer's instructions and according to following standards:

- EN 205: 2003 Adhesives. Wood adhesives for non-structural applications. Determination of tensile shear strength of lap joints.
- EN 302-1: 2004 Adhesives for load-bearing timber structures. Test methods. Part 1: Determination of bond strength in longitudinal tensile shear strength.
- EN 385: 2003 Finger jointed structural timber. Performance requirements and minimum production requirements.
- EN 408: 2010 Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties.

Test samples for shear strength were prepared in laboratory and samples for bending strength in industrial conditions. Strength at 20 °C was determined without heating at general laboratory conditions. Thermal stability in shear and bending strength at selected temperatures, 50, 80 and 110 °C was determined immediately after removing of samples from the heat chamber according to the standard:

- EN 14257: 2006 Adhesives. Wood adhesives. Determination of tensile strength of lap joints at elevated temperature (WATT '91).

Longitudinal tensile shear strength was carried out on the testing equipment LaborTech 4.050 and bending strength on TIRAtest 2850 (Figure 1). All test results were subjected to mathematical and statistical analysis (KLEIN *et al.* 2002).

Fig. 1 Testing equipment with inserted samples.

RESULTS AND DISCUSSION

Lap joints

Table 1 describes basic statistical evaluation of obtained results of shear strength of lap joints of beech wood samples glued with PUR adhesive Jowapur 686.60 measured at different levels of temperature.

Tab. 1 Shear strength of lap joints of beech wood glued with PUR adhesive.

Temperature (°C)	Shear strength (MPa)	Std deviation (MPa)	Variability (%)	Number of samples
20	11.6	1.71	14.8	10
50	11.7	1.03	8.8	10
80	9.8	1.95	19.9	10
110	8.7	1.48	16.9	10

Detailed statistical analysis of Duncan's test showed a statistically significant difference in shear strength of beech PUR glued joints between the temperatures of 50 and 80 °C. The temperature of 80 °C caused the significant decrease of shear strength of glued joint of beech wood samples. Shear strength of glued joints at temperatures above 80 °C fell below the standard EN 301 requirement of 10 MPa.

Table 2 describes basic statistical evaluation of obtained results of shear strength of lap joints of spruce wood samples glued with PUR adhesive Jowapur 686.60 measured at different levels of temperature.

Tab. 2 Shear strength of lap joints of spruce wood glued with PUR adhesive.

Temperature (°C)	Shear strength (MPa)	Std deviation (MPa)	Variability (%)	Number of samples
20	6.8	1.26	18.6	10
50	5.9	1.12	18.9	10
80	5.8	1.22	19.9	10
110	5.5	1.02	16.9	10

Detailed statistical analysis of Duncan's test showed a statistically insignificant difference in shear strength of spruce PUR glued joints between the temperatures of 20 and 110 °C for spruce wood samples. The increase in temperature caused only a slight decrease in shear strength of bonded lap joints of spruce wood. When comparing beech PUR with spruce PUR adhesive joins, we can conclude that PUR adhesive showed a good thermal stability up to 50 °C; the shear strength of the beech PUR joints was not significantly decreased. At 80 °C shear strength decreased to the value below the standard EN 301 requirement. Slower decrease in shear strength was found at PUR spruce joints. The increasing temperature caused only a slow decreasing of shear strength of PUR bonded spruce lap joints (see Fig. 2). All these results of testing of lap glued joints for both wood species are comparable with results of CLAUSS *et al*. (2011b), who stated the first decrease of shear strength over 50 °C, further increasing of temperature over 200 °C caused delamination of glued joints. Table 3 describes the basic statistical evaluation of obtained results of shear strength of lap joints of beech wood samples glued with PVAC adhesive measured at different levels of temperature. Detailed statistical analysis of Duncan's test showed the statistically significant difference in shear strength of beech PVAC glued joints among all levels of used temperatures, see Fig. 2. Shear strength of beech PVAC glued joint at 20 °C is statistically significantly different from the shear strength at all other tested temperatures. With temperature increased to 50 °C, shear strength was strongly decreased. Temperature of 80 °C caused the significant decrease of shear strength; shear strength of beech PVAC glued joints fell below the standard product requirements of 7 MPa.

Tab. 3 Shear strength of lap joints of beech wood glued with PVAC adhesive.

Temperature (°C)	Shear strength (MPa)	Std deviation (MPa)	Variability (%)	Number of samples
20	10.4	2.86	27.5	10
50	7.1	0.92	13.0	10
80	5.4	0.78	14.3	10
110	1.9	0.61	32.7	10

Table 4 describes basic statistical evaluation of obtained results of shear strength of lap joints of spruce wood samples glued with PVAC adhesive measured at different levels of temperature.

Tab. 4 Shear strength of lap joints of spruce wood glued with PVAC adhesive.

Temperature (°C)	Shear strength (MPa)	Std deviation (MPa)	Variability (%)	Number of samples
20	5.8	1.66	29.0	10
50	5.9	0.93	15.9	10
80	4.8	0.69	14.5	10
110	2.0	0.63	31.2	10

Statistical analysis of Duncan's test showed the statistically insignificant differences in shear strength of spruce PVAC glued joints on temperature levels of 20, 50 and 80 °C. The increased temperature caused only a slight decrease in shear strength of bonded lap joints of spruce wood. Statistically significant difference was confirmed between shear strengths measured at 20 and 110 °C. The temperature of 110 °C caused the significant decrease of shear strength of spruce PVAC glued joint, see Fig. 2. When comparing beech PVAC with spruce PVAC adhesive joins, we can see that beech PVAC adhesive showed strong decrease in shear strength at 50 °C (by 32 %). The strength of the joints at 110 °C reached the value only 18 % of the shear strength of the joint at 20 °C. Spruce PVAC joints showed better stability in temperature interval from 20 °C to 50 °C. Up to 80 °C the shear strength of spruce PVAC joints did not change significantly. At 80 °C the shear strength reached 72 % of spruce wood strength. At 110 °C the shear strength dropped to 34 % of the initial value of spruce PVAC shear strength.

Based on the measured values of shear strength (see Fig.2), we can conclude that decrease of shear strength is much stronger at PVAC adhesive. Final strength of PVAC joints (at 110 °C) reached the value of only 1.9 MPa at beech (18 %) and 2 MPa at spruce (34 %). The percentage is calculated considering the initial values of the shear strength of particular adhesive bonds. PVAC belongs to the group of thermoplastic polymers which are able to deform reversibly within a special temperature range. If the range is exceeded, a thermal degradation occurs. Final strength of PUR adhesive bonds (at 110 °C) reached the values of 8.7 MPa for beech (75 %) and 5.5 MPa for spruce (81%) wood samples.

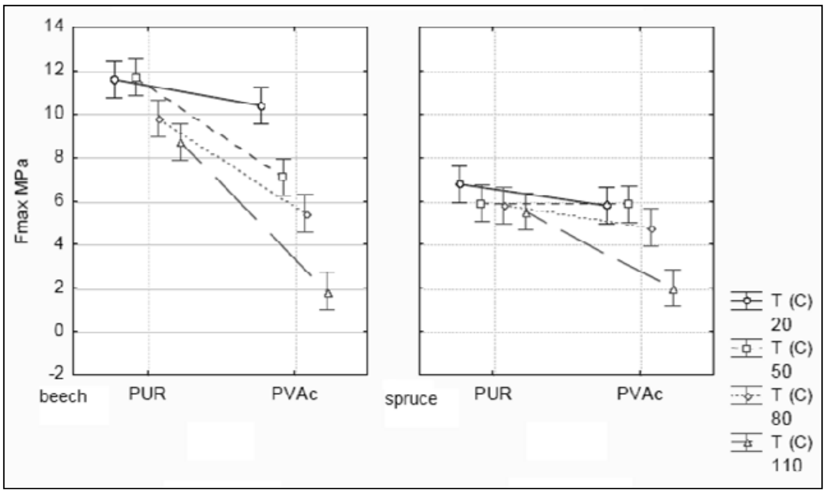

Fig. 2 Shear strength of lap joints in beech and spruce specimens glued with PUR and PVAC adhesives at different temperatures.

Finger joints

Table 5 describes basic statistical evaluation of obtained results of bending strength of finger joints of spruce wood samples glued with PUR adhesive Kestopur 1030 measured at different levels of temperature.

Tab. 5 Bending strength of finger joints of spruce wood glued with PUR adhesive.

Temperature (°C)	Bending strength (MPa)	Std deviation (MPa)	Variability (%)	Number of samples
20	41.7	11.50	30.0	6
60	34.2	9.96	31.7	6
80	36.3	2.56	7.0	6
110	35.3	7.96	24.4	6

Despite the high coefficient of variation, all values of bending strength of all tested spruce PUR finger joint samples were over the standard requirement. Bending strength of glued finger joints at increased temperatures generally did not fall below the standard EN 385 requirement of 24 MPa. Table 6 describes basic statistical evaluation of obtained results of bending strength of finger joints of spruce wood samples glued with MUF adhesive measured at different levels of temperature.

Tab. 6 Bending strength of finger joints of spruce wood glued with MUF adhesive.

Temperature (°C)	Bending strength (MPa)	Std deviation (MPa)	Variability (%)	Number of samples
20	50.3	5.0	9.93	6
60	43.1	5.71	13.24	6
80	38.5	3.34	8.67	6
110	31.1	3.56	11.44	6

Bending strength of all tested spruce MUF finger joint samples met the standard requirement. Bending strength of glued spruce MUF finger joints at increased temperature never fell below the standard EN 385 requirement of 24 MPa. The tested MUF adhesive is commonly used for bonded wood for load bearing constructions. It is certified in combination with the hardener according to EN 301.

When comparing the bending strength of finger joints glued with PUR and MUF adhesives we can conclude that finger joints of both adhesives show a good thermal stability up to 110 °C. At temperatures below 80 °C, the bending strength of spruce MUF finger joins is higher than bending strength of spruce PUR finger joins. The results are comparable with results published by FOLLRICH *et al.* (2007), who stated slowly higher shear strength values of MUF-bonded samples when compared with PUR and phenol-resorcinol-formaldehyde bonded specimens. Up to 110 °C none sample showed bending strength below the standard EN 385 requirement of 24 MPa. When testing the thermal stability of lap joints of beech wood, CLAUS *et al.* (2011b) stated excellent thermal stability of MUF adhesives up to 70 °C, a slight drop of shear strength at 110 °C, while the wood failure percentage was up to 200 °C 100 %. The lower shear strengths were caused by the failure of wood and not by the failure of the adhesive.

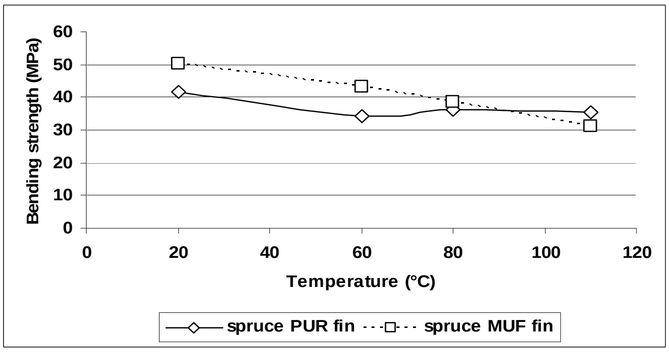

Fig. 3 Bending strength of finger joints in spruce specimens against temperature.

When increasing the temperature (see Fig. 3), the bending strength of spruce PUR finger joints showed slow decrease. Similar behaviour was observed at MUF adhesive, but the bending strength of spruce MUF finger joints at temperature above 60 °C decreased faster.

CONCLUSION

The importance of this work lies in pointing out the fact that glued joints may be under conditions of elevated temperature weak points of wooden structures. The aim of the experiments was to determine the behaviour of glued joints and their thermal resistance at temperatures, which can be increased at general conditions e.g. sunshine, heating of buildings, chimney from fireplace etc. Heat resistance of joints was tested at 20, 50, 80 and 110 °C. Both types of polyurethane adhesives showed a slight decrease in shear strength at elevated temperature. It was proved, that temperatures up to 110 °C do not reduce the strength of bonded joints under standard requirements. Bending strength of glued finger joints, glued with PUR and MUF adhesives, at increased temperatures up to 110 °C always met the standard. Within carried experiments, PVAC had to be considered separately, as it is thermoplastic adhesive used for non-bearing applications.

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